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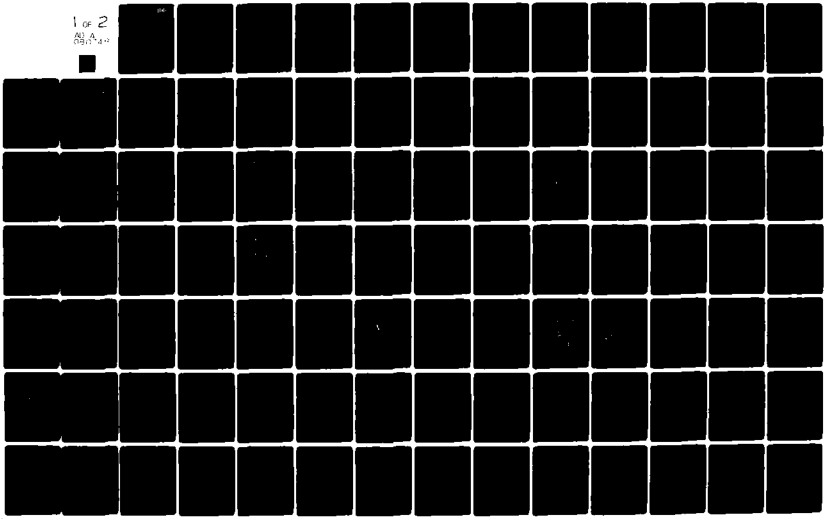

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TURBOPROPULSION COMBUSTION TECHNOLOGY ASSESSMENT

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Combustor Design	Combustion Chemistry	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report co~~nsists of five sections which serve~~ to summarize an the findings of the assessment ~~team~~. Section I provides a general introductory overview of the state-of-combustion-technology today and highlights some general projections and trends for the future. Section II gives a state-of-the-art review of the five special topic areas of interest covered during the assessment -- main burners, afterburners, combustion modeling, structural and mechanical design, and alternative fuels. Sections III and IV examine the advanced technology trends and projected technology needs, respectively, as related to each of the

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topic areas cited above. A five-year technology plan is outlined in Section V.

Future aircraft propulsion requirements call for combustion systems capable of: 1) accepting greater variations in compressor discharge pressure temperature and airflow, 2) producing heat release rates and temperature rises which will ultimately approach stoichiometric levels, and 3) providing high operational reliability and improved component durability, maintainability and repairability. In addition, the new requirements associated with exhaust emissions and fuel flexibility must be addressed. Consequently, as the combustor designer is confronted with the new requirements of the future, especially exhaust emissions and fuel flexibility, new design concepts may be required to provide an acceptable solution. Engineers in the aero propulsion combustion community will certainly enjoy challenges with the possiblity for imaginative solutions as the next quarter century unfolds. The remainder of this report will highlight where the state-of-the-art of turbopropulsion combustion lies today and what technology trends and needs must be realized to meet tomorrow's propulsion system requirements.

FOREWORD

During 1978, a joint USAF/Navy/Army Combustion Technology Assessment Team was formed to conduct a special evaluation of the turbopropulsion combustion area. The Combustion Technology Group of the Turbine Engine Division, Air Force Aero Propulsion Laboratory (AFAPL), was the lead organization for this assessment and had prime responsibility for organizing and directing all activities related thereto.

Technology assessments are common to most fields of research and are often used to provide information which will guide and justify the selection of objectives and avenues of approach for future research. Industry and Government often have had different purposes and goals for their exploratory development efforts. These differences, and the sometimes haphazard exchange of information between Industry and Government, have caused both to occasionally direct their efforts in a less than optimal manner. Consequently, this assessment was formulated to gain a better understanding of the detailed engineering conducted by the aircraft gas turbine engine industry. A better understanding would enable the Laboratory to better prepare and justify its fiscal 1980 program plan and subsequent-year exploratory development efforts in gas turbine combustion technology.

This Technology Assessment consisted of a formalized review and evaluation of the current state-of-the-art and projected technology needs in combustion and was based primarily upon inputs received from five selected engine companies: Pratt & Whitney Aircraft Group (Government Products Division), Detroit Diesel Allison (General Motors Corporation), General Electric Company, AiResearch Manufacturing Company of Arizona, and Teledyne-Continental Aviation and Engineering Corporation.

An "open-to-ideas" policy was pursued in this assessment. The more quickly newer and better technologies can be brought forward and extended, the more quickly the capabilities of both the gas turbine engine industry and the Air Force can be improved.

Consequently, industry input in support of this technology assessment was sought to develop a more unified perspective from which to direct near- and far-term technology efforts.

Inputs from each company were presented to the combined-service assessment team as part of a formal on-site meeting with each company. Both oral and written responses were provided to the team based on a special questionnaire/inquiry package which was developed by the AFAPL Combustion Technology Group and provided to each company prior to their on-site visit (see Appendix). The inquiry package was generally organized into three sections. Of primary importance were the first two sections which would: 1) serve to establish the current level of turbopropulsion combustion technology and the design methodology related thereto; and 2) define the direction and the suggested technology needs for future exploratory development. The third section, a historical assessment characterizing past combustion system design and performance, was carried as an appendix to the questionnaire. The historical data would serve to provide a technical base and a historical perspective of the industry from which the Air Force could support and justify programs for the development of new technology. The organization conforms to specific goals of the Aero Propulsion Laboratory's Combustion Technology Group; however, this technology assessment has also stimulated the interest of other services within the Department of Defense, specifically the Army and Navy. Consequently, representatives from the Combustion Technology Areas of these services as well participated in this assessment.

The editors wish to thank the authors who participated in the preparation of this assessment report. Their specific contributions are acknowledged below:

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SECTION I
INTRODUCTION

This report consists of five sections which serve to summarize the findings of the assessment team. Section I provides a general introductory overview of the state-of-combustion-technology today and highlights some general projections and trends for the future. Section II gives a state-of-the-art review of the five special topic areas of interest covered during the assessment -- main burners, afterburners, combustion modeling, structural and mechanical design, and alternative fuels and exhaust emissions. S tions III and IV examine the advanced technology trends and projec d technology needs, respectively, as related to each of the topic areas cited above. A five-year technology plan is outlined in Section V.

The ultimate results of this assessment are to define turbine engine combustor needs which will provide the technology necessary to meet projected Air Force mission requirements and for mission elements to identify basic propulsion system requirements for which necessary combustion technology can be defined.

The late 1980 and early 1990 Air Force projected strategic, tactical and reconnaisance-intelligence mission areas will require advancements in airbreathing propulsion. These general mission categories include the development of gas turbine engines which are more efficient and exhibit higher performance. Two of the key turbine engine technologies are primary combustion and efficient augmentation technology for selected high thrust conditions. For example, in the strategic area, aircraft propulsion in general would utilize an augmented medium to high bypass ratio turbofan. A multi-mixed mission cruise missile may also require some type of augmented turbine engine. Tactical aircraft propulsion requirements, however, would utilize, low to medium bypass engines with augmentation, as necessary, for air superiority and survivability. This would call for a high performance, compact augmentation system and could be either a duct burner or advanced technology afterburner. On the other hand, for high speed reconnaisance-intelligence vehicles the augmentator would be a major component

of the propulsion system because of the limitations of the turbomachinery at very high speeds. A duct burner would be the most probable selection for this application.

1. MAIN BURNERS

The evolution of aircraft gas turbine combustion technology over the past forty years has been extremely impressive. While the combustion system was the primary limitation in development of the first aircraft gas turbine, the complexity and hardware costs associated with current rotating engine components (compressor and turbine) now far exceed that of the combustion system. Recent developments, however, have once again caused significant shifts in development emphasis toward combustion technology. New concepts and technology improvements will be necessary to satisfy recently legislated exhaust pollutant regulations. Moreover, future emphasis on engines which can utilize fuels with a broader range of characteristics is expected to require additional combustor technology development.

Beyond these externally imposed requirements are the combustion system performance improvements necessary to keep pace with new engine developments. Further reductions in combustor physical size and weight are expected to continue as firm requirements. Performance improvements, especially with respect to engine thrust/weight ratio and specific fuel consumption, will require higher combustor temperature rise, greater average turbine inlet temperatures, and closer adherence to the design temperature profile at the turbine inlet. High performance designs must also permit greater Mach number operation within and around the combustor, but not at the expense of increased combustion system pressure loss. Costs (both initial and operational) must be minimized, as recent experiences with high temperature engines have confirmed the necessity to consider reliability and maintenance aspects of life cycle cost as well as performance and fuel consumption.

In recent years, significant technological advancements have been realized in both combustion system design and performance. With respect to the important design parameters of combustion

efficiency, pressure loss, combustor size and pattern factor, the annular combustors recently developed have provided substantial improvements. Further improvements in these parameters will be required, however, if propulsion system demands of the future are to be met.

2. AUGMENTORS

Many aircraft weapon systems today require substantial increases in thrust capability (50-100%) for short durations to meet takeoff, acceleration and tactical maneuvering requirements. These requirements are most easily met by the addition of an augmentor to the propulsion system. The afterburner is a relatively simple thrust augmentation device, which when added to the propulsion system can be used to enhance the flexibility of the basic gas turbine cycle. The principal advantage to using the afterburning gas turbine is that the weight of the augmented engine is much less than that of a turbojet engine operating at the same maximum thrust.

The turbine engine augmentor is essentially a large low pressure combustion system, and as such, presents a broad range of unique design and performance problems. There are three classes of augmentors today (Figure 1): the turbojet augmentor, the turbofan augmentor and the turbofan duct burner. The first two have undergone considerable development and operational use over the past 20 years, while the duct burner has not yet been fully developed. As flight Mach numbers continue to increase, however, the requirement to develop the duct or ram burner system will be necessary.

The most important design and performance parameters for the augmentor are combustion efficiency, system pressure loss, weight, ignition/relight and combustion stability. The latter, combustion stability, relates to the coupled acoustic/combustion response of the augmentor to pressure and flow perturbations during augmentor operation and has been the subject of intense research and development in recent years. Early turbojet afterburners often suffered from high frequency acoustic pressure oscillations known as "screech." These oscillations can be driven by the combustion

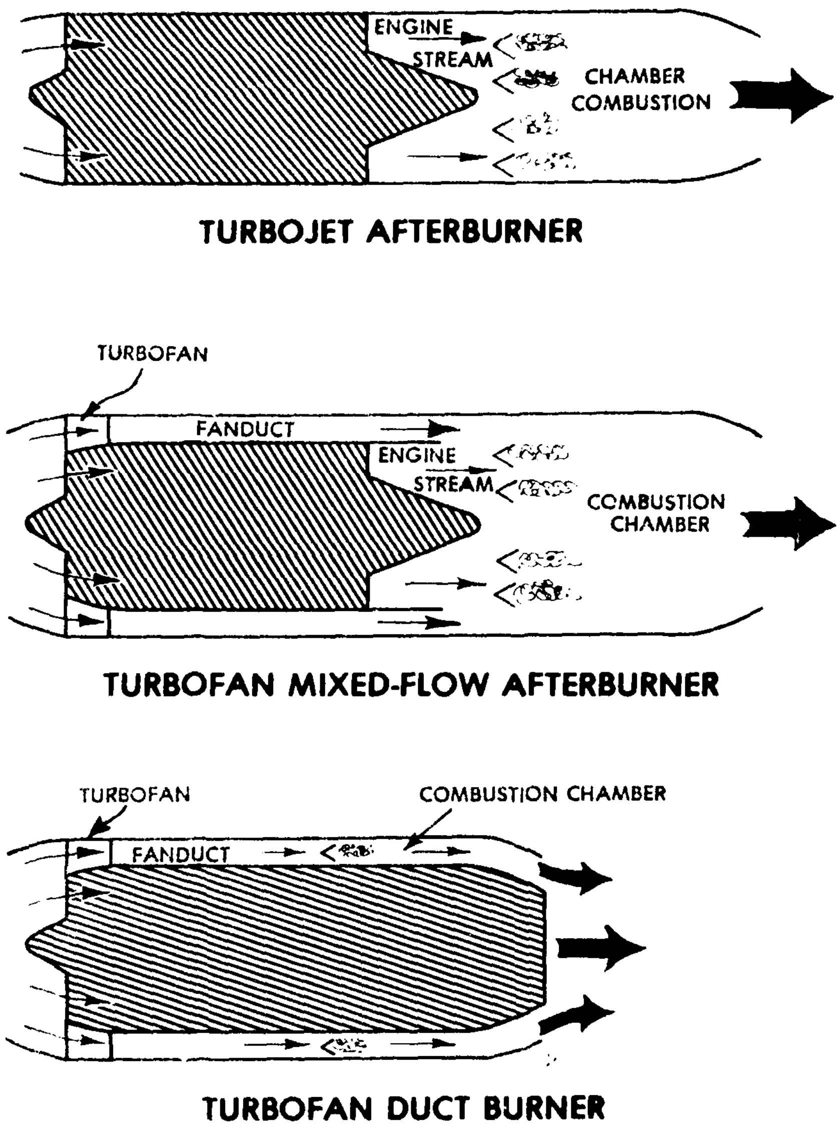

Figure 1 Principal Classes of Augmentors

process causing local regions of high heat transfer to the afterburner liners and flameholding system. If not effectively controlled, catastrophic failure of the augmentor hardware can occur. Perhaps the simplest control technique still routinely used today is the screech liner -- a perforated liner located in the vicinity of the flameholding region acting as an acoustic suppressor. With the advent of the turbofan augmentor, however, a new stability phenomenon known as "rumble" was introduced. Rumble is a low-frequency instability characterized by longitudinal pressure oscillations. These oscillations can propagate directly to the fan through the long bypass duct causing reduced surge margin, fan stall or even fan/augmentor coupling increasing pressure oscillation amplitudes to catastrophic levels. Unfortunately, the suppression of these low frequency oscillations cannot be accomplished using conventional high-frequency screech liners. Consequently, the USAF and Navy embarked on a major analytical/experimental research program to gain a better understanding of the design and performance mechanisms which cause or contribute to the onset of rumble in the turbofan augmentor. These Services, however, continue to require further improvements in component performance capability and operational reliability to meet projected mission requirements for both strategic and tactical aircraft weapon systems. Hence, a principal technology requirement defined for the augmentor calls for the development of a compact, low pressure loss, high combustion efficiency design capable of rumble-free operation at all flight conditions.

3. COMBUSTION MODELING

The complexity of the aerothermodynamic and chemical processes occurring simultaneously in the combustor prevent a purely analytical approach to component design and performance prediction. Insufficient capability to accomplish measurements of importance within the combustor has precluded all but the most basic understanding of practical gas turbine combustion processes. As a result, one has had little choice but to formulate new designs largely on the basis of personal or organizational experience. Continuation of this approach to combustor design for high

temperature sophisticated systems under development today and in the future would be extremely costly and time consuming. The turbine engine industry can no longer afford to conduct component development activities on a generally empirical basis. Hence, significant R&D programs are now being directed toward developing improved analytical design procedures reinforced by more powerful measurement diagnostics.

The principle objective of the combustion system model is to analytically describe and predict the performance characteristics of a specific system design based on definable aerodynamic, chemical and thermodynamic parameters. Many modeling approaches describing the flow field characteristics of a particular combustion system have evolved over the past twenty years. Early models were almost entirely empirical while the newest models currently under development are based more on fundamental principles. Improved computer availability and capability as well as more efficient numerical techniques have had a significant impact on combustion modeling by permitting the more complex, theoretically based approaches to be considered.

Development of valid combustor models is often hampered by a difficulty in acquiring data for use in comparing and refining analytical solutions. Different types of measurements are required to validate various aspects of the important submodels, i.e., droplet size distribution, turbulence intensity, etc. In addition, improved instrumentation will be necessary to support the combustor development process. Such equipment will provide improvements and eventually the final design. The rapidly growing field of combustion diagnostics will play an increasingly important role in satisfying the needs. Conventional thermocouple and sampling techniques have been previously utilized to study combustion processes in practical systems. However, additional application and technique refinements are necessary. For example, new laser-based combustion diagnostic measurement equipment can be expected to play an increasingly important role in the future.

STRUCTURAL AND MECHANICAL DESIGN

Past trends in turbine engine combustor structural/mechanical designs were accomplished by selecting the highest temperature

sheet material available at the time and by providing appropriate cooling as required. Testing of selected configurations would then identify the major areas of distress and past experience would dictate necessary fixes. As a result, this trial and error structural development approach has contributed to the notion that the combustor design process is a "black art." With the continued push for higher temperature engines, however, it has become increasingly difficult to extrapolate long life designs using past experience. The higher temperature combustors require more air for combustion, leaving less for liner and structural cooling. Hence, advancements in cooling technology and utilization of improved high temperature superalloy materials are required. Reduced available cooling air is in direct conflict with past mechanical/structural design practices of adding cooling air to fix an endurance problem. Today, increased emphasis is being placed on the area of hot parts durability and life. Recent advancements in liner cooling designs have added substantially to the maintainability and durability aspects of the combustor at a time when system operating pressures and temperatures are on the rise. Figure 2 illustrates the technological improvements realized in the ten to fifteen years since annular combustors were introduced. For example, the continued drive for reduced cost, improved fuel economy and design compactness and simplicity has led to the compact, high temperature combustor of the F101 engine (originally developed for the B-1 Bomber) illustrated in Figure 3. This combustor is a low pressure loss (5.1%), high heat release (8.5 $\times 10^6$ BTU/hr/atm/ft^3) design employing an improved low pressure fuel injection system, a machined-ring high durability liner and a simple, cast, low-loss inlet dump diffuser. Relative to other contemporary combustion systems, the F101 is the most advanced annular design developed to date and introduces a new family of compact, high temperature systems for fighter, bomber and transport applications.

The trends cited above -- shorter length, higher temperatures, less cooling air -- dictate a more stringent reliance on analytical tools (heat transfer, stress/strain analysis, life prediction),

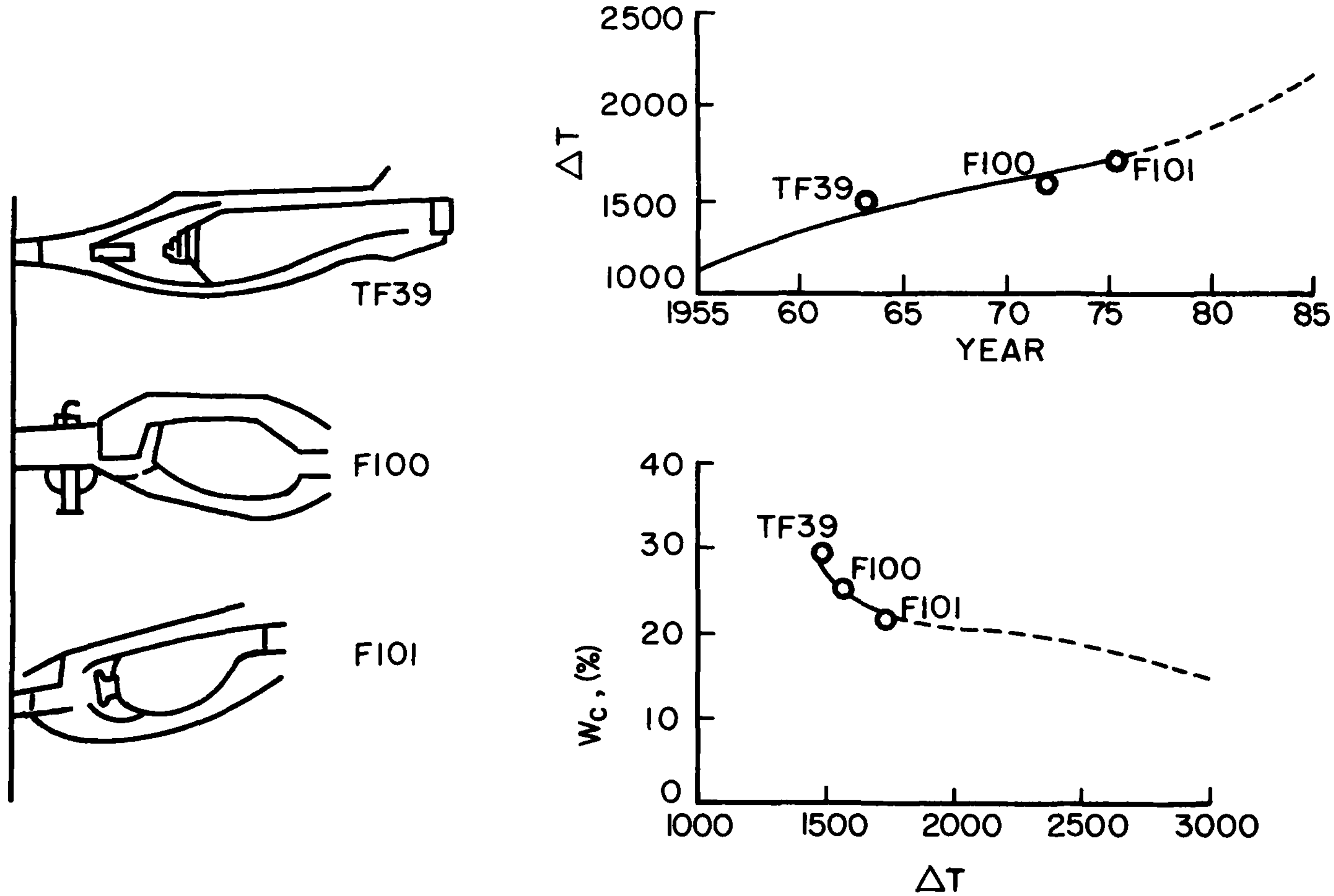

Figure 2 Advancements in Combustor Technology

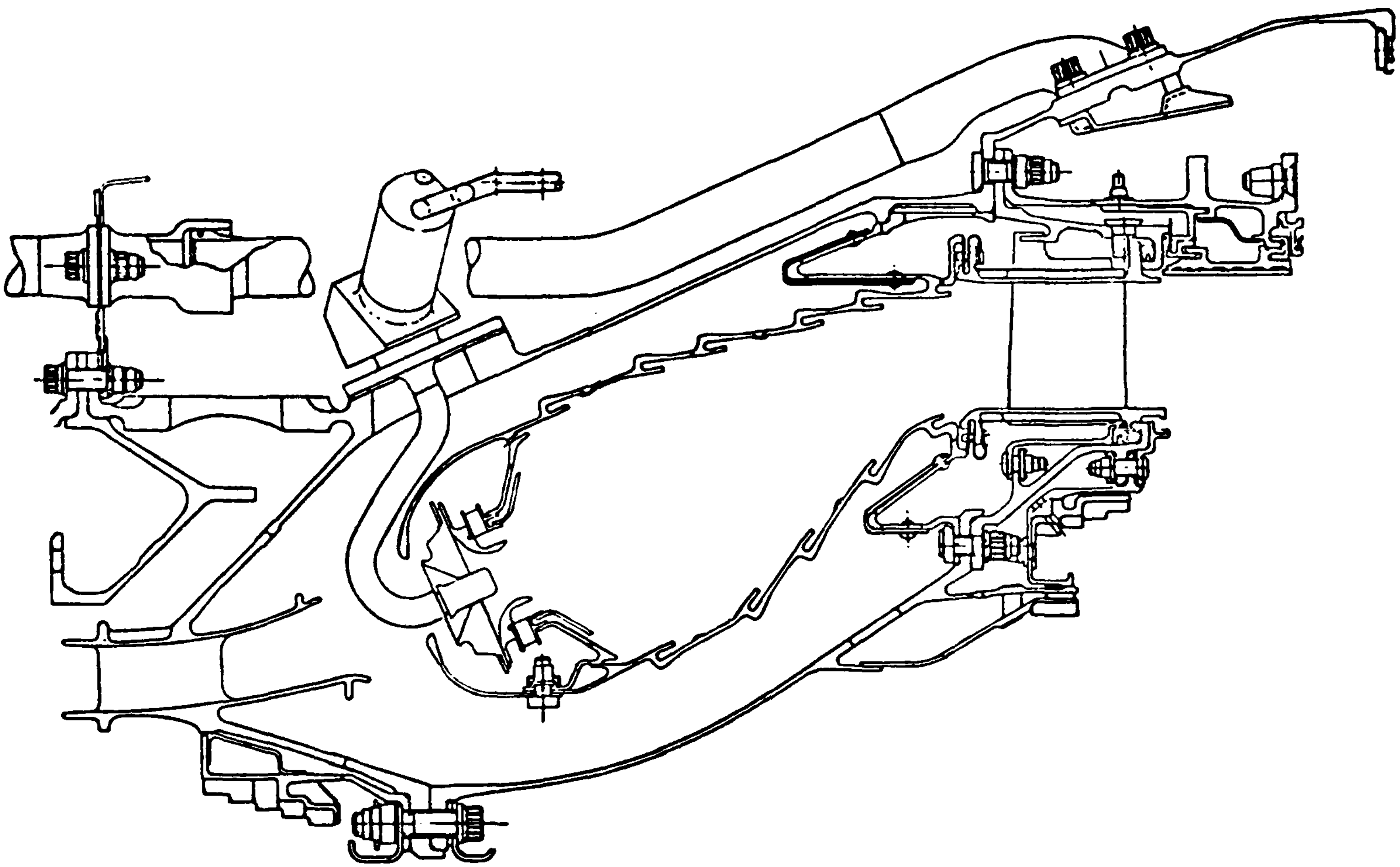

Figure 3 Compact F101 Engine Combustor

test data collection/correlation, material development/characterization and manufacturing process improvements than have been achieved in the past. Stress analysis and fatigue life prediction capabilities are of particular concern. Advances in turbine cooling and life enhancement and higher performance cycle designs are now requiring combustors to last longer at higher temperatures. Consequently, combustor life prediction techniques must be improved both to optimize life and minimize development cost.

5. ALTERNATIVE FUELS AND EXHAUST EMISSIONS

The aero propulsion combustion community is currently confronted with two new and difficult challenges: reduction of exhaust pollutant emissions and accommodation of fuels which will reduce cost while increasing availability. Unfortunately, these two areas form a dichotomy. Nearly all alternative fuel sources today tend to increase one or more undesirable exhaust pollutants formed during combustion. Consequently, it is anticipated that realizing maximum availability of an attractive alternative fuel source (shale, coal, etc.) while minimizing chemical emissions may require some compromise to both.

a. Alternative Fuels

In recent years, the cost and availability of aircraft jet fuels have drastically changed. Per gallon, jet fuel costs are more than six times the 1973 cost for both commercial and military consumers. In addition, fuel procurement actions have encountered difficulties in obtaining desired quantities of fuel, even though significantly reduced from 1972 consumption levels. These developments have encouraged initial examinations of the feasibility of producing jet fuels from nonpetroleum resources.

Although economics and supply are primarily responsible for this recent interest in new fuel sources, projections of available world-wide petroleum resources also indicate the necessity for seeking new means of obtaining jet fuel. Regardless of current problems, the dependence on petroleum as the primary source of jet fuel can be expected to cease sometime within the next half century.

If the general nature of future aircraft (size, weight, flight speed, etc.) is to remain similar to today's designs, liquid hydrocarbons can be expected to continue as the primary propulsion fuel. Liquified hydrogen and methane have been extensively studied as alternatives but seem to be practical only for very large aircraft. The basic nonpetroleum resources from which future liquid hydrocarbon fuels might be produced are numerous. They range from the more familiar energy sources of coal, oil shale and tar sands to possible future organic material derived from energy farming. Some of the basic synthetic crudes, especially those produced from coal, will be appreciably different from petroleum crude. For example, reduced fuel hydrogen content would be anticipated in jet fuels produced from these alternative sources.

Because of the global nature of aircraft operations, jet fuels of the future are likely to be produced from a combination of these basic sources. Production of fuels from blends of synthetic crudes and natural crudes may also be expected. In light of the wide variations in materials from which world-wide jet fuel production can draw, it is anticipated that economics will dictate the acceptance of future fuels with properties other than those of currently used JP-4, JP-5 and Jet A. Consequently, much additional information will be required to identify the fuel characteristics of these broad specification fuels.

b. Exhaust Emissions

With the advent of environmental regulations for aircraft propulsion systems, the levels of carbon monoxide, unburned hydrocarbons, oxides of nitrogen and smoke in the engine exhaust become important. Naturally, the environmental constraints directly impact the combustion system -- the principal source of nearly all pollutants emitted by the engine. Major changes to combustor design philosophy have evolved in recent years to provide cleaner operation at all conditions without serious compromise to engine performance. Although no specific environmental regulation or emissions limitations have been imposed on military aircraft propulsion systems, all future weapon systems

are to be designed with minimum chemical exhaust emissions and nonvisible exhaust plumes. Environmental assessments are now required of each new engine system and efforts are being made throughout the development program to minimize exhaust pollutants, but without serious impact to required engine performance and operational requirements.

Future aircraft propulsion requirements call for combustion systems capable of: 1) accepting greater variations in compressor discharge pressure, temperature and airflow, 2) producing heat release rates and temperature rises which will ultimately approach stoichiometric levels, and 3) providing high operational reliability and improved component durability, maintainability and repairability. In addition, the new requirements associated with exhaust emissions and fuel flexibility must be addressed. Consequently, as the combustor designer is confronted with the new requirements of the future, especially exhaust emissions and fuel flexibility, new design concepts may be required to provide an acceptable solution. Engineers in the aero propulsion combustion community will certainly enjoy challenges with the possibility for imaginative solutions as the next quarter century unfolds. The remainder of this report will highlight where the state-of-the-art of turbopropulsion combustion lies today and what technology trends and needs must be realized to meet tomorrow's propulsion system requirements.

SECTION II
STATE-OF-THE-ART

This section is intended to provide a general review of the current state-of-the-art of turbopropulsion combustion. It serves to establish a technical base or benchmark from which the subsequent sections on technology trends and needs are developed. As cited in the Introduction (Section I), five principal areas are assessed: main burners, augmentors, combustion modeling, structural and mechanical design and alternative fuels and exhaust emissions.

1. MAIN BURNERS

This section attempts to define a state-of-the-art technology level for main burners, including inlet diffusers and fuel nozzles, as a baseline from which to study current design trends and ultimately to assess future technology needs. Twenty-three production engine combustors dating from the mid-1950's to the present were surveyed. Some of the combustion systems considered did not enter production, but were included in this review as demonstrations of available technology. A few of the combustors examined were designed for short life; hence, where appropriate, data for these systems were either stated as "short life" or were excluded from the discussions altogether.

The following presents a review of the three principal combustor components: the liner, the fuel injection system and the inlet diffuser. Considerable information was provided during the assessment regarding the liner and was examined for trends relative to the following combustor design parameters:

- Cycle pressure ratio
- Combustor flow parameter
- Specific combustor volume
- Modified space heating rate
- Burner temperature rise (BΔT)
- Burner outlet temperature (BOT)
- Liner cooling effectiveness
- Liner specific surface area

- Liner specific weight
- Liner cooling airflux

Only limited information was presented on the fuel injection system and inlet diffuser. For these, brief state-of-the-art summaries are provided.

a. <u>Combustor Liner</u>

Selection of a combustor geometric type and subsequent detail design is highly dependent on the mission requirements of the overall engine. For large engines, can-annular combustors have largely given way to annular designs; for small to moderate power engines, single can-type combustors can, in some cases, compete with small annular or reverse-flow annular configurations. For all designs, it was noted that combustor lengths have decreased over the years as space heating rates, burner inlet temperatures and pressures, and burner outlet temperatures have increased. Short compact combustors are advantageous from the standpoint of engine weight and rotor dynamics and also permit the liner to withstand higher gas temperatures with the same amount of cooling air, or perhaps less. As combustor exit temperatures increase, however, more judicious use of available cooling air has become necessary, resulting in advanced liner configurations of ever-increasing complexity. Consequently, both liner cost and weight have increased in recent years.

Combustor size reduction has been the dominant trend. It has followed the trend of increasing cycle pressure ratio enhanced by the introduction of the bypass turbofan engine. In the 1950's, the highest engine pressure ratios were approaching 12 (J57-P20 = 11.7), while today's engines have pressure ratios in the upper twenties (Figure 4). The introduction of the turbofan, and subsequently the high bypass turbofan engines, have permitted reductions in combustor physical airflow required to attain a specified engine thrust level. Moreover, since turbofan engine cycles optimize at much greater pressure ratios than do turbojet cycles, the combustor flow parameter, (F.P.)* required to attain

*(F.P. = $W_a\sqrt{T_{t_3}}/P_3$ where W_a is combustor inlet airflow, lbm/sec; T_{t_3} is compressor exit total temp., °R; and P_{t_3} is compressor exit total pressure, lbf/in^2.)

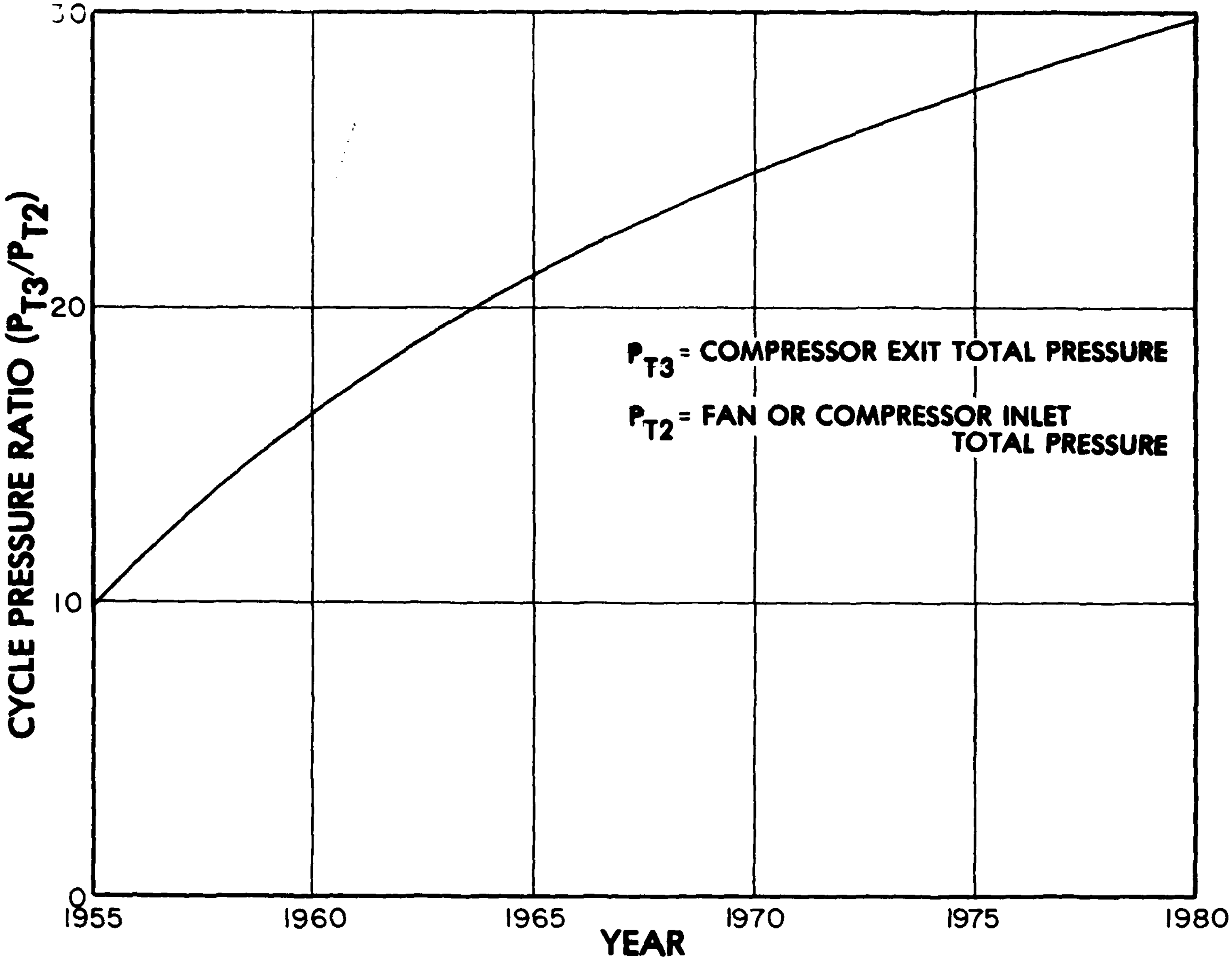

Figure 4 Engine Trend in Cycle Pressure Ratio

a specified thrust has been dramatically reduced (flow parameter is more meaningful than physical airflow because flow parameter establishes the flow area required for a specified flow field Mach number, and hence, establishes the combustor size). For example, the highest design point flow parameter surveyed was 35.6 for the J57-20 turbojet engine which operates at a pressure ratio of 12 and produces 11,400 pounds of dry thrust. Application of today's technology to a low bypass turbofan engine having the same dry thrust and a pressure ratio of 21 results in a flow parameter of only 8-11, while a high bypass turbofan engine at the same pressure ratio and thrust exhibits a flow parameter of 4-5. Thus, a combustor for a modern high bypass turbofan could have a flow area of only one-eighth that of yesterday's turbojet, if flow Mach number were held constant; combustor volume reduction is more dramatic because combustor length is also reduced.

Reductions in combustor flow parameter normalized to engine dry thrust are graphically illustrated as a function of engine pressure ratio (Figure 5). Four distinct engine families are depicted: the turbojets and the low, medium, and high bypass turbofans. Significant reductions in combustor flow parameter occur as engine pressure ratio and bypass ratio increase, resulting in corresponding reductions in combustor size and volume.

As discussed above, the observed reduction in combustor flow due to engine cycle evolution and increased pressure have permitted reductions in combustor size. These size reductions have also offered benefits to the engine design, such as shorter length and lower weight, and have driven advancements in combustor technology through reductions in combustor surface area and height. As shown in Figure 6, airflow-specific combustor volume (volume/combustor flow parameter) has decreased from 0.29 ft^3-sec/lbm for the J52-P8 to as low as 0.043 ft^3-sec/lbm for the J85-21, with the majority of modern combustors falling within 20 percent of 0.1 ft^3-sec/lbm. This reduction is due in part to increased rates of reaction and fuel vaporization, stemming from cycle pressure ratio increases. Rates of fuel atomization and fuel/air mixing tend to determine combustor size at high values

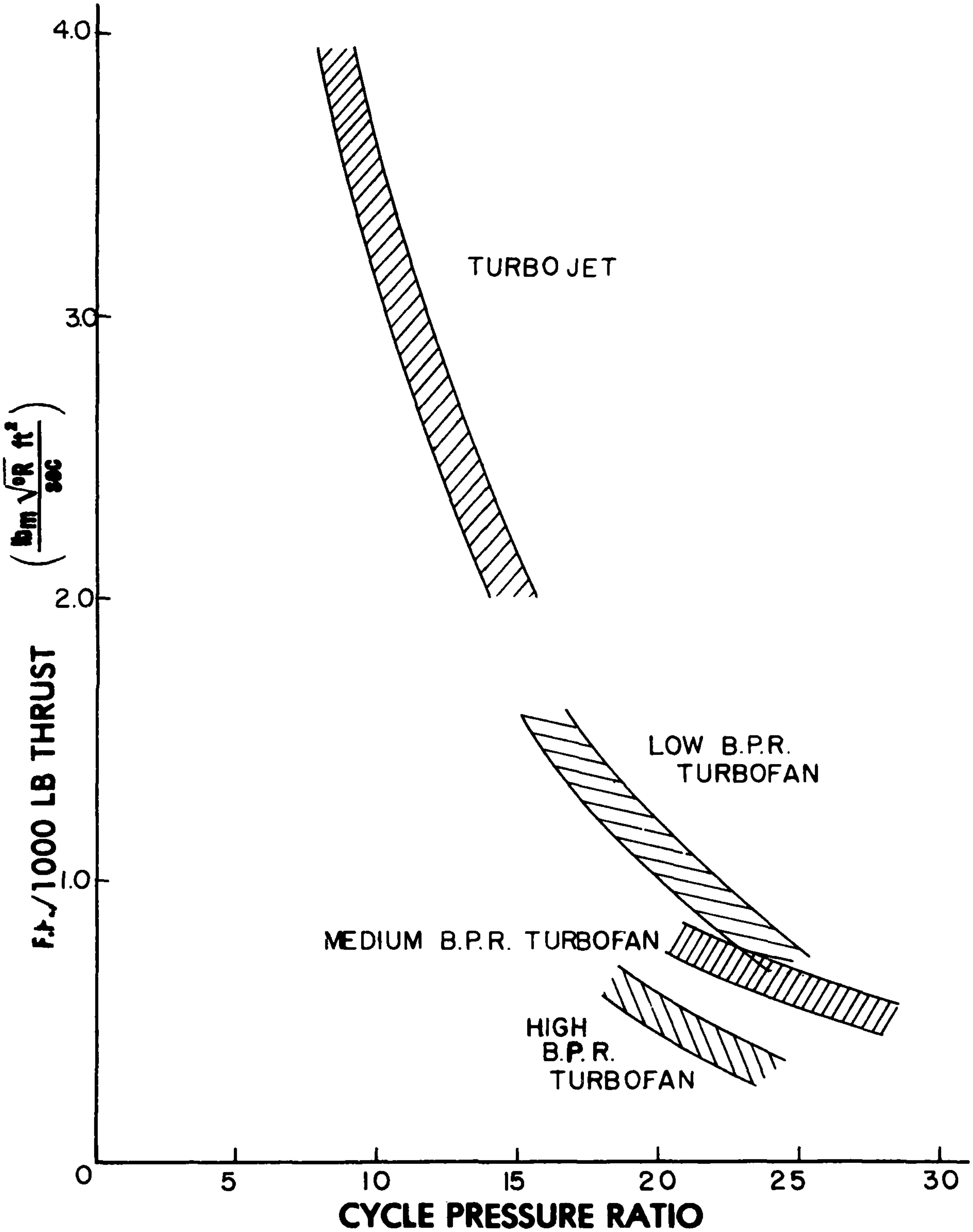

Figure 5 Effect of Bypass Ratio and Cycle Pressure Ratio on Combustor Flow Parameter

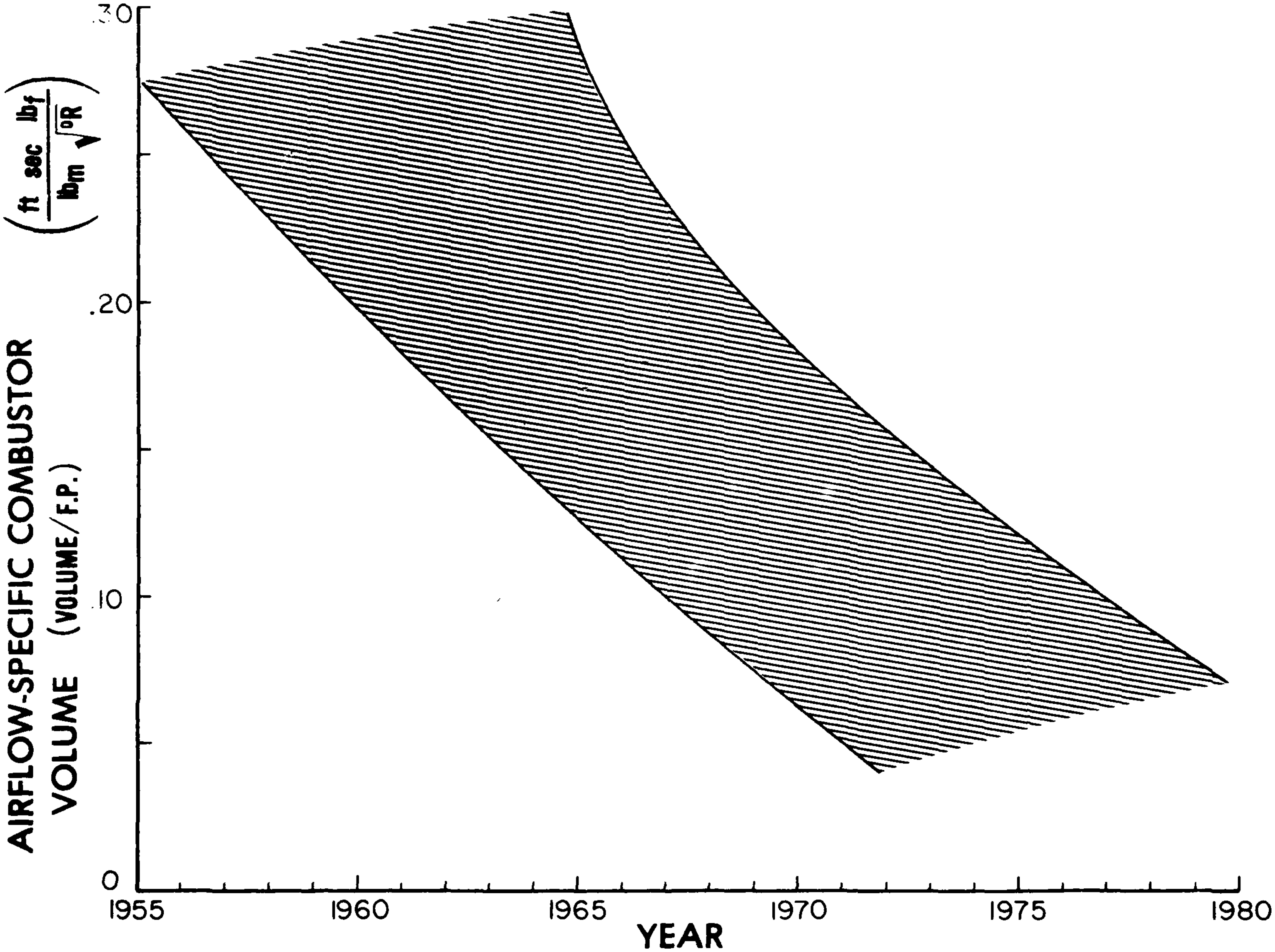

Figure 6 Trend in Specific Combustor Volume

of cycle pressure, and these rates have been enhanced through use of strongly swirled primary zones and airblast fuel injection, leading to additional combustor volume reductions.

Space Heating Rate (BTU/hr-atm-ft^3) or more properly, Modified Space Heating Rate[1], can also be used as a measure of technical progress in reducing combustor size. Modified space heating rate (BTU/hr-atm-ft^2) eliminates space rate superiority associated with smaller combustors due to their high surface area/volume ratios. Modified space heating rates for today's combustors are as high as 8.5×10^6 (F101) as opposed to 4×10^6 (J57-20) for combustors of the 1950's (Figure 7). However, since some combustors are designed with very little intended payoff due to size, there will always be some low space rate combustors.

Adequate liner cooling has always been a problem, but in light of the required increase in burner temperature rise (BΔT) over the past few years, less air is available for dilution and liner cooling, and hence, the problem is aggravated. In the 1950's, BΔT's were at the 1100 to 1200°F level indicating that up to 75% of the burner airflow was available for dilution and liner cooling. Modern day production engine BΔT's, however, are now in the 1500 to 1700°F level (Figure 8) with only approximately 60-65% of the air available for dilution and cooling (Figure 9).

As available cooling air is decreased, it becomes more difficult to cool the liner. Liner cooling is also made more difficult by increasing burner outlet temperature (BOT) because, in simple terms, the average temperature of the gases in the burner increases, thereby increasing the liner heat load. BOT has increased from a 1500°F level of 1956 vintage engine to the current level of 2600°F (Figure 10).

The degree of difficulty in cooling the liner can be quantified approximately by the required liner cooling effectiveness

$$\varepsilon = \frac{BOT - T_{METAL\ MAX}}{BOT - T_3} \tag{1}$$

where $T_{METAL\ MAX}$ = the liner design hot spot temperature

T_3 = compressor exit temperature

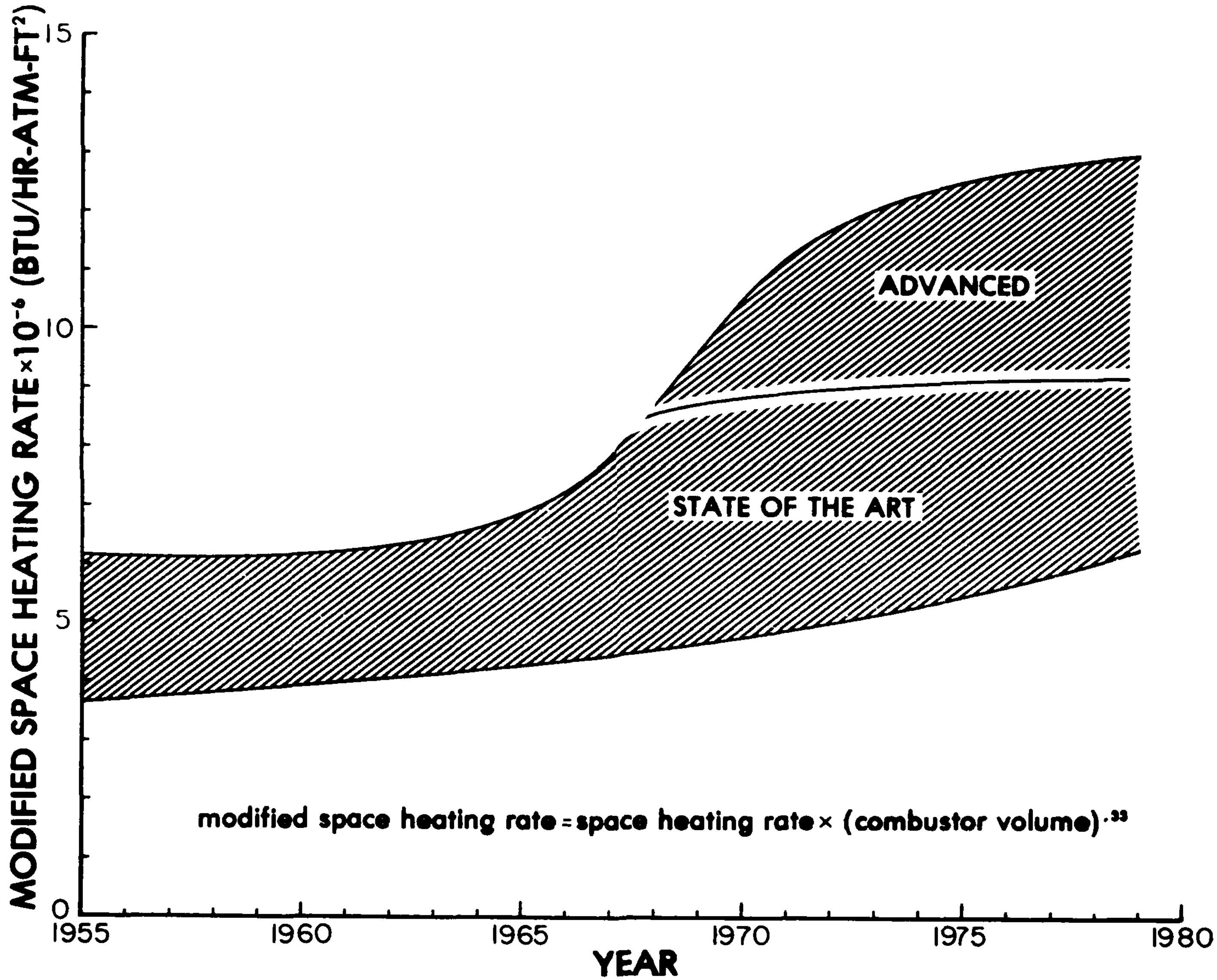

Figure 7 Trend in Combustor Modified Space Heating Rate

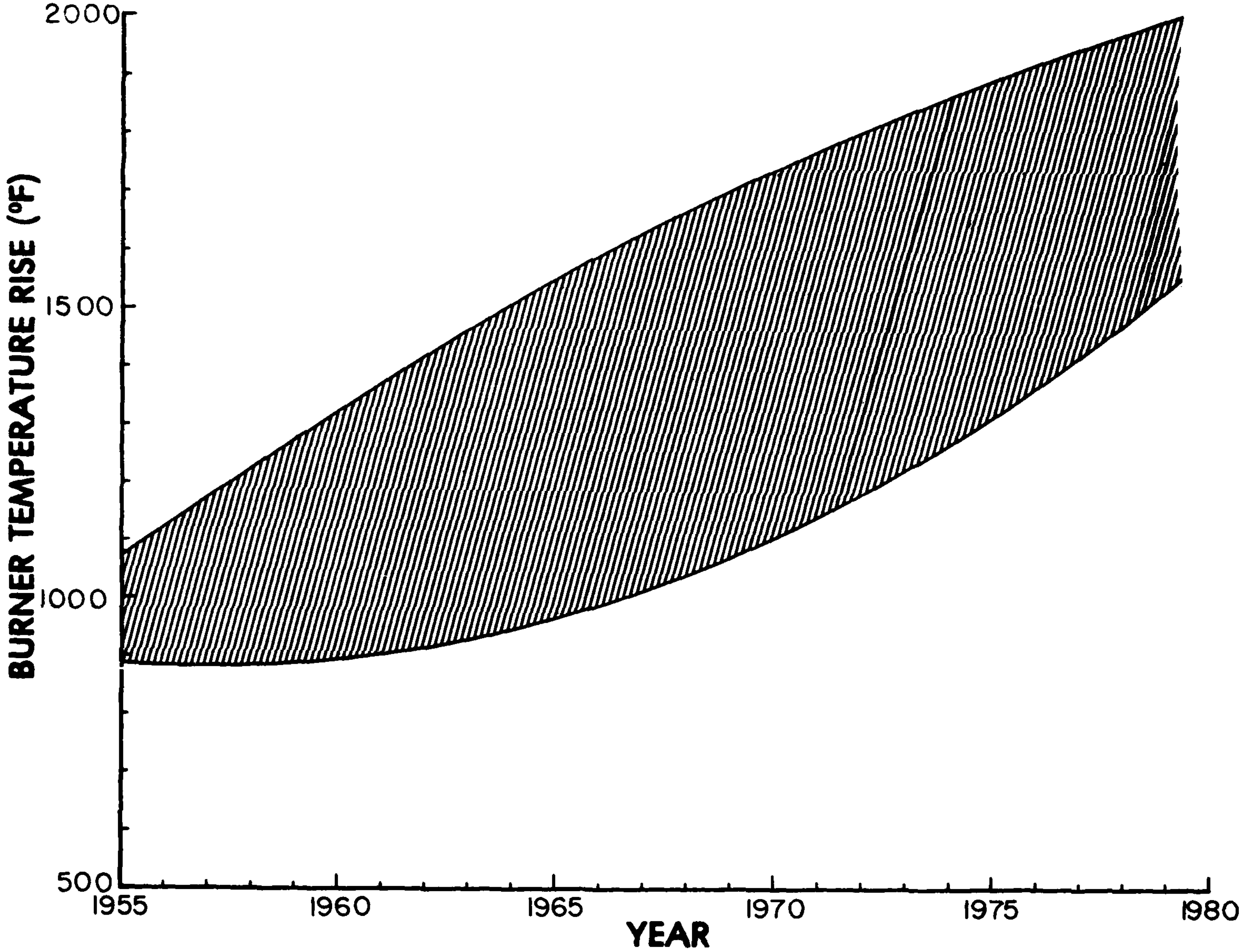

Figure 8 Trend in Burner Temperature Rise

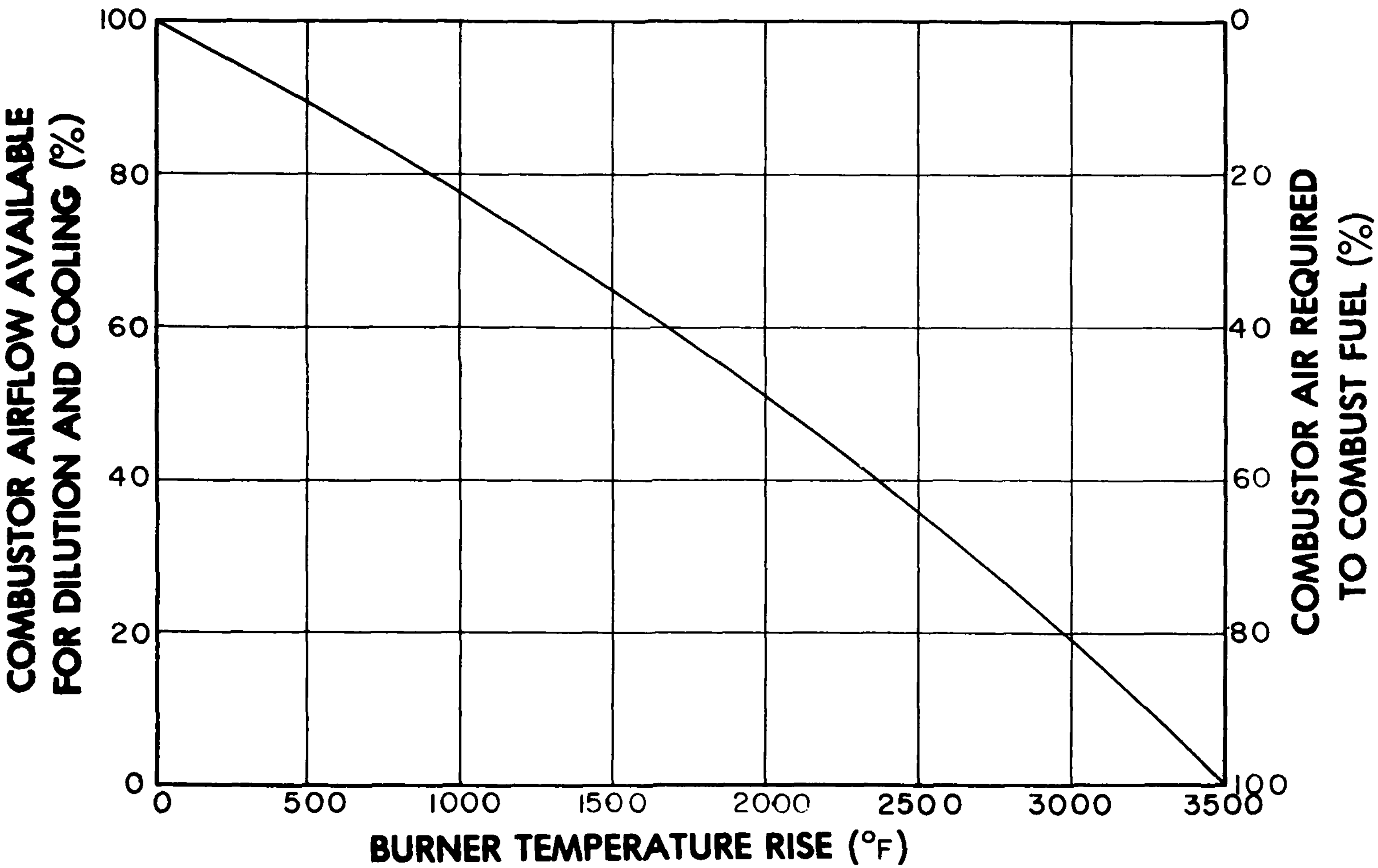

Figure 9 Impact of Required Burner Temperature Rise on Air Availability

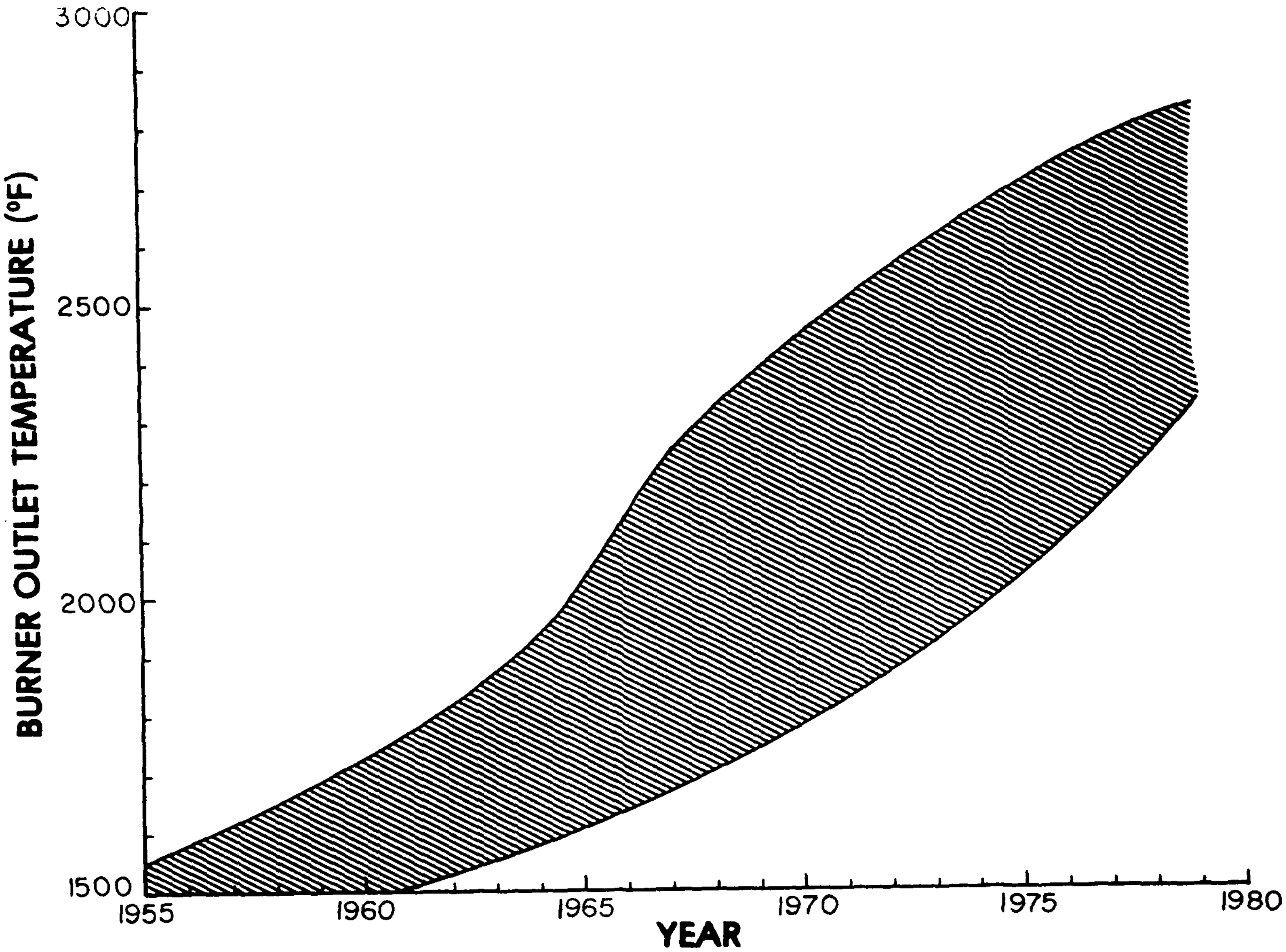

Figure 10 Trend in Burner Outlet Temperature

In the combustor primary zone, BOT may be replaced by flame temperature; hence, the value of ε generally decreases from the primary zone to the burner exit. Required liner cooling effectiveness has increased from 0.1 in 1956 to 0.6 for current production engines (Figure 11). This increase in required liner cooling effectiveness has resulted primarily from BOT increases because, while BOT increased by 1100°F (from 1500°F to 2600°F), T_3 increased by only 300°F (from 700°F to 1000°F), and the allowable liner metal temperature remained essentially constant. The dependence of required liner cooling effectiveness on BOT is shown in Figure 12.

Today's production engine liners are subjected to a greater heat load, yet a smaller percentage of the burner inlet air is available for cooling. Two factors have contributed to the solution of the liner cooling problem. First, the liner surface area per pound of burner airflow (specific liner surface area) has been significantly reduced over the years due to both the liner volume reduction previously shown and the liner surface area reduction associated with changing from can-annular to annular burner designs (Figure 13). Liner specific surface area, based on combustor flow parameter, was reduced by a factor of two; it was reduced by a factor of three, based on physical airflow. This means that more air is currently available for cooling and dilution per unit surface area in spite of the percentage reduction in available air.

The second factor contributing to the solution of the liner cooling problem is the dramatic advancements made in liner cooling technology in recent years. Referring again to Figure 12, it can be seen that increases in BOT and the attendant required increases in liner cooling effectiveness were accomplished with improved liner cooling techniques. Today's production engines operating at 2500 to 2600°F utilize a film-cooled liner. Its cooling characteristics are superior to the earlier louver film-cooled designs (thimble or wigglestrip) of the 1950's because the cooling air is more accurately metered, resulting in a more effective hot-side coolant.

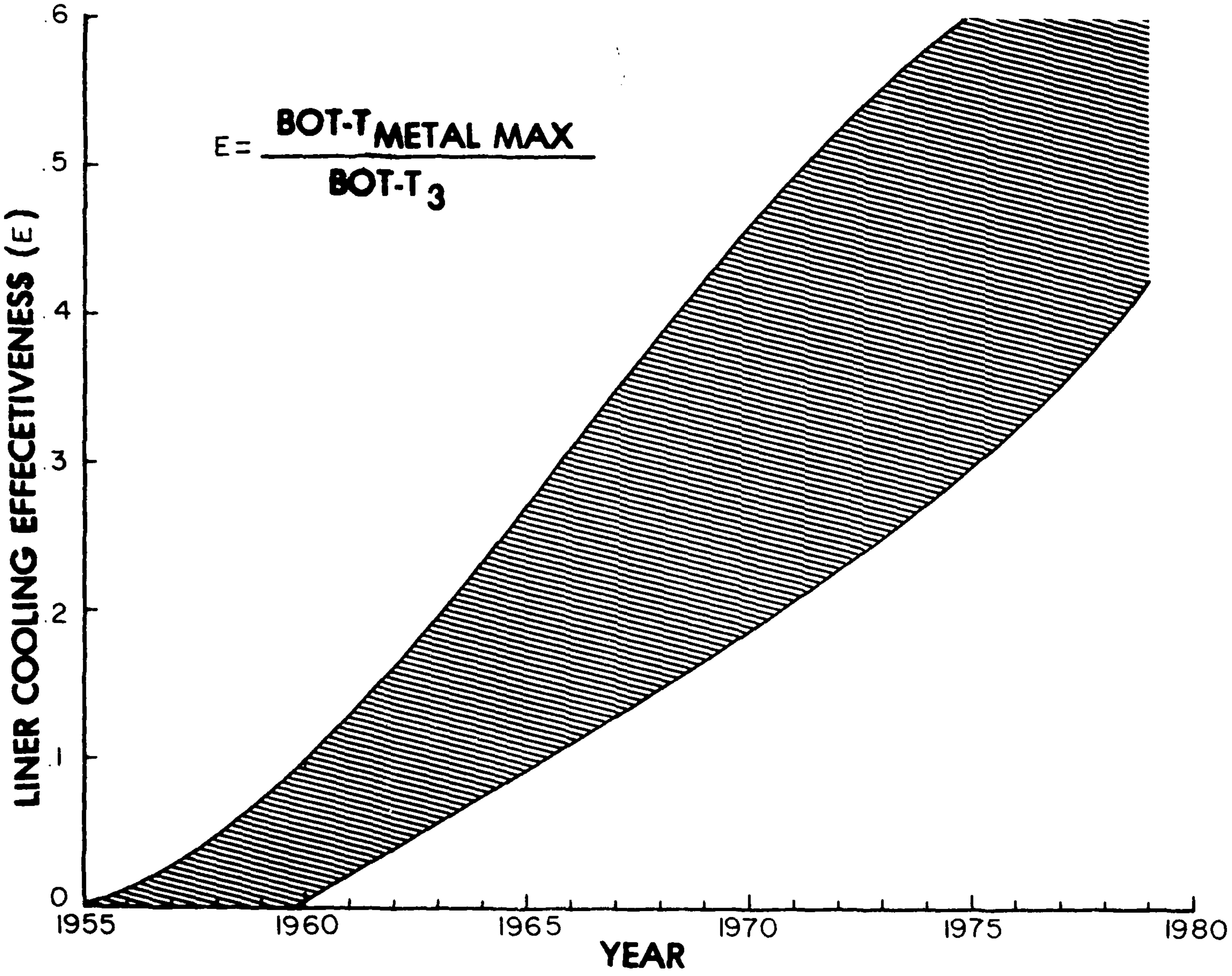

Figure 11 Trend in Liner Cooling Effectiveness

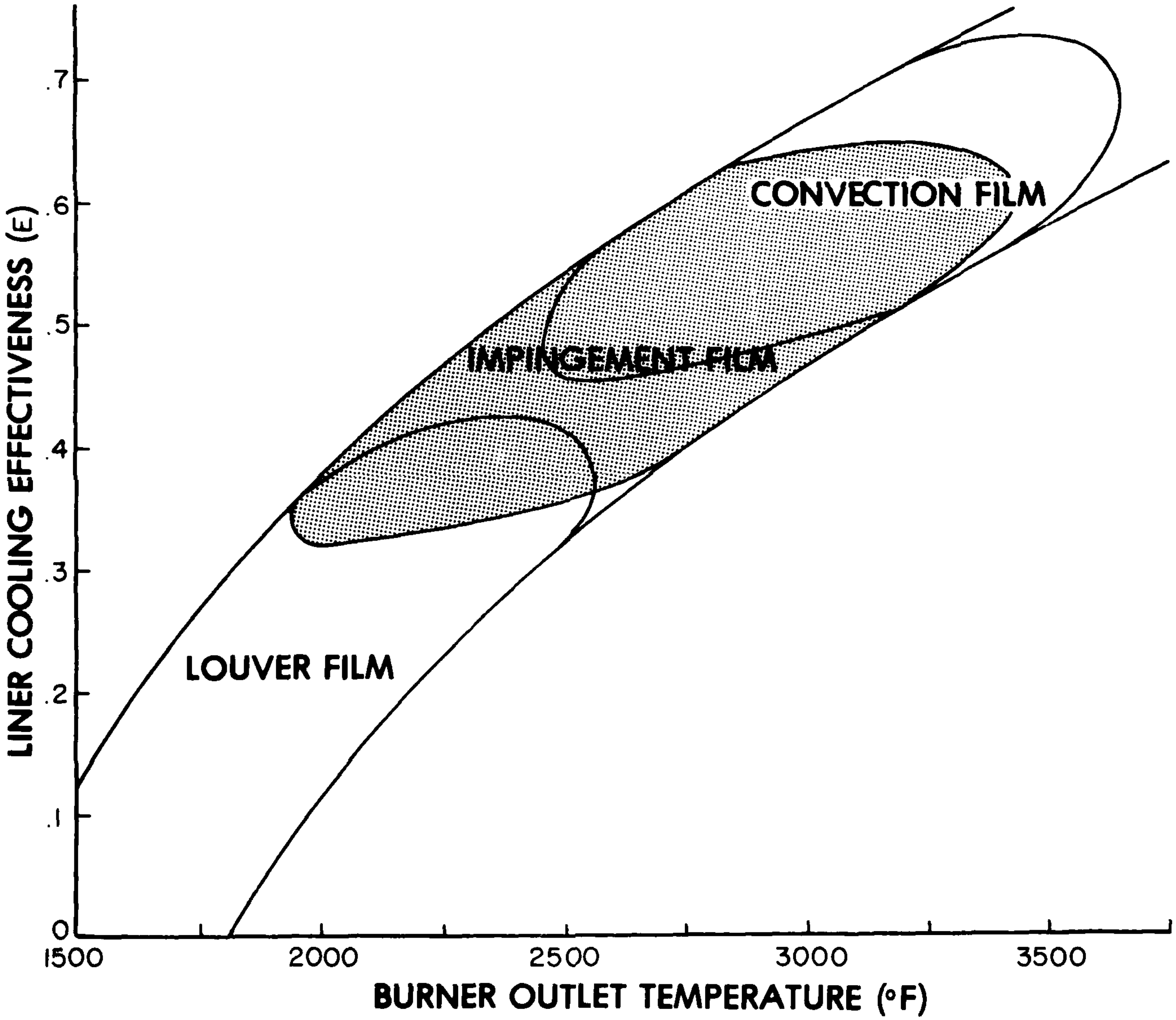

Figure 12 Effect of Burner Outlet Temperature and Cooling Type on ε

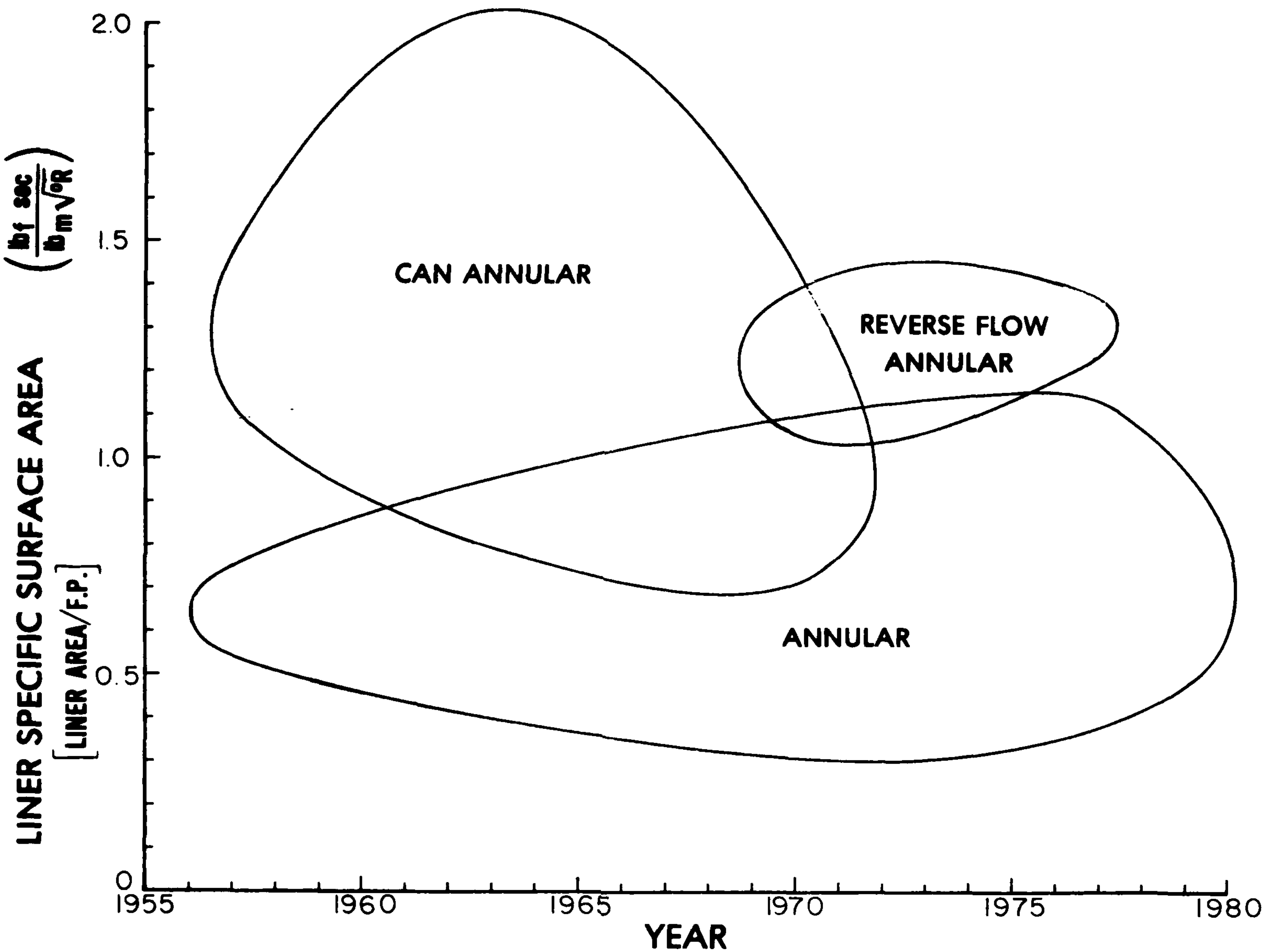

Figure 13 Effect of Burner Type on Liner Surface Area

Improvements in cooling characteristics are often accompanied by increases in liner specific weight, shown as a function of BOT in Figure 14. Engines of the 1950's required very little liner cooling, operated at BOT's of 1500-1600°F and contained liners having specific weights of from 1 to 4 lb/ft^2. Today's liners operating at BOT's of 2600°F require liners having specific weights of approximately 7 lb/ft^2. Liner specific weight further increases when multiple walls are utilized in order to obtain improved cooling. Short-life liners for missile and drone applications generally exhibit a significant weight savings because of the short time at temperature (<10 hours) and the virtual absence of thermal cycles (especially when terrain-following is not part of the required mission).

A measure of how well a combustor liner must be cooled can be quantified by the liner cooling effectiveness parameter, ε, as defined earlier by Equation (1). For a specific combustor environment, liner cooling effectiveness <u>attained</u> is primarily governed by two basic items: cooling air flux and liner heat transfer design. Figure 15 illustrates how improvements in cooling effectiveness may be achieved: (1) by increasing cooling air flux for a fixed liner design (i.e., path A of the louver film-cooled liner) or (2) by changing to an improved liner geometry (i.e., path B, shifting from the louver to the impingement film-cooled liner) while maintaining a fixed cooling air flux. With increases in burner outlet temperature, the value of required cooling effectiveness is increased. Consequently, the louver-cooled designs can no longer meet acceptable life requirements, and by necessity, a change to more advanced cooling geometries which can meet these higher effectiveness levels is required. Future combustor liners are expected to employ impingement film cooling, convection film cooling or perhaps even transpiration cooling techniques, all of which can provide higher cooling effectiveness for a fixed cooling air flux.

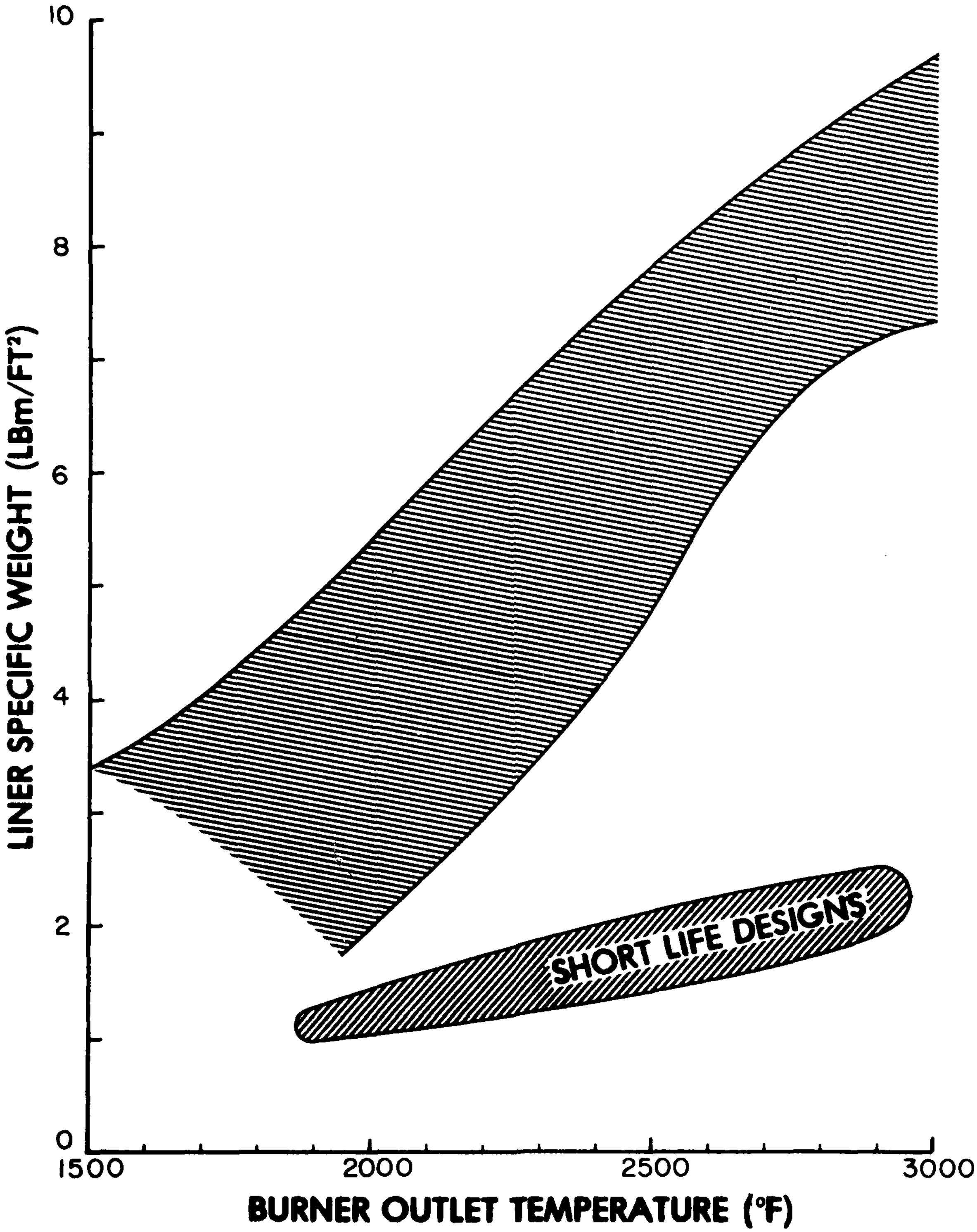

Figure 14 Effect of Burner Outlet Temperature on Liner Weight

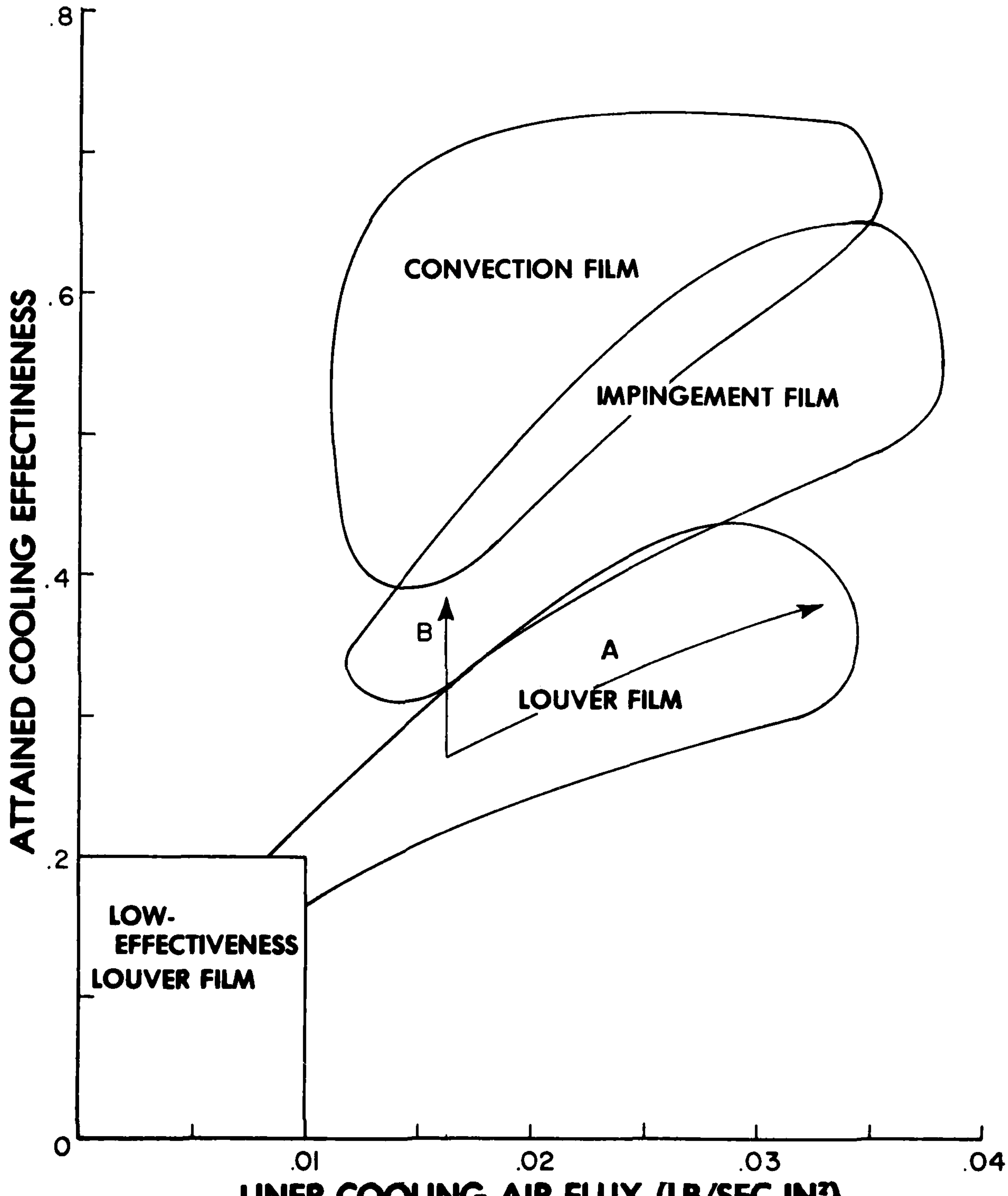

Figure 15 Effect of Cooling Technique on Cooling Air Flux and Liner Cooling Effectiveness

b. Fuel Injection

The objective of the fuel injector is to provide a finely atomized spray of fuel droplets in order to promote rapid vaporization and mixing for subsequent fuel/air burning in a short length. In the 1950's, fuel atomization was accomplished primarily by pumping the fuel through pressure atomizing fuel nozzles at very high pressure (1000-1500 psi). In the early 1960's, swirlers were introduced around each fuel nozzle to accelerate atomization, vaporization and fuel/air mixing using airflow aerodynamic forces. It was recognized, however, that obtaining good fuel atomization using high pressure fuel systems can be a costly method. They not only contribute to engine cycle inefficiency, but pump life, metering orifice contamination and acquisition costs are often directly proportional to discharge pressure.

Airblast fuel injection appeared in production engines in the early 1970's with the advent of the F100, TF-34 and T700 engine systems. This injection technique makes direct use of the aerodynamic forces provided by the inlet air stream to initiate rapid fuel/air mixing. As illustrated in Figure 16, a small portion of the high velocity inlet air is passed through the fuel injector. A high shear region is established at the point where fuel is introduced promoting very rapid fuel atomization and mixing. Consequently, the air blast technique can provide finely atomized fuel with lower injector differential pressures; and the degree of fuel/air mixing can be enhanced. Hence, the airblast fuel injector represents the state-of-the-art of today's fuel injection systems.

c. Inlet Diffuser

The function of the combustor inlet diffuser is to slow compressor air from Mach numbers as high as .3-.4 to Mach numbers in the range of .1-.15 with minimum loss in total pressure. The combustor requires low flow velocities in order to sustain and stabilize combustion and to permit adequate residence time for mixing and burning of the fuel and air. For much of the period considered, contoured-wall diffusers have been used to achieve low pressure losses. For this design, however, careful

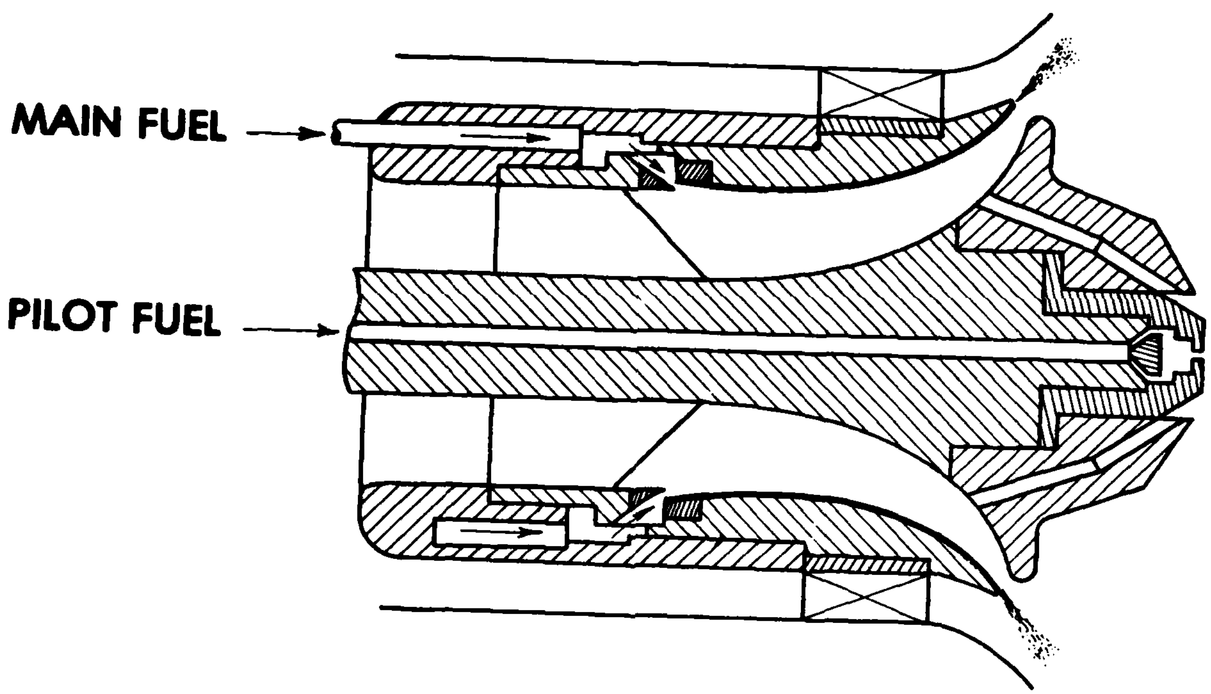

Figure 16 Airblast Fuel Injector

attention must be given to the precise selection of airflow splits between passages, for example, to control flows between the inner and outer walls of an annular combustor while avoiding boundary layer flow separation.

Production engine combustor diffusers today are either of the contoured-wall type or of the rapid expansion, dump design. Although contoured-wall diffusers can be more efficient than the dump type provided the passageways are large enough to preclude flowpath distortion/boundary layer separation, the state-of-the-art for production engines is generally considered to be the dump diffuser. The short length dump diffuser is also becoming more acceptable today from an overall engine standpoint; and the attendant higher diffuser pressure losses and combustor reference velocities are being tolerated in order to achieve better aerodynamic flow stability in the combustor while reducing the weight and length of the engine shafting, combustor and cases, etc.

Advanced technology trends and supporting technical needs for main burners are discussed in Sections III and IV, respectively. The state-of-the-art and design methodology described herein serve to establish a base of departure from which both design and performance trends can be projected. In addition, any effects due to changes in fuel specification and the introduction of alternative fuels must be a part of the design and performance considerations for main burners in the future.

2. AUGMENTORS

The thrust produced by a gas turbine engine may be augmented to 50% or more by afterburning or reheating the exhaust gases from the main or core engine. Increasing the temperature and velocity of these exhaust gases by afterburning provides for greater propulsion system operational flexibility. Afterburning provides an aircraft with additional capabilities such as reduced takeoff distances, increased rates of climb and sustained supersonic flight.

Historically, afterburners have been the final portion of the engine to be designed. Augmentor designers generally do not accurately know the operating conditions of the main engine

until all core design iterations are complete. Current afterburning turbofan engines can provide as much as 30,000 pounds of thrust with augmentation ratios of 1.75 or more. Given turbine exhaust temperatures of approximately 1800°R, a temperature increase of nearly 2500° can be achieved in the afterburner section for a turbofan engine. Augmentor pressure losses with and without heat addition average approximately 10% and 4%, respectively.

Maintaining stable, resonance-free combustion during afterburner operation remains the most serious problem in today's turbofan engine state-of-the-art design. Screech (high frequency) and rumble (low frequency) combustion instabilities limit augmentor performance in its operation throughout a required flight envelope. A number of perturbation sources in and around the engine can contribute to the onset of combustion instability during augmentor operation (Figure 17). Thus, the need exists for the design and development of compact, low pressure loss and highly efficient afterburners which can operate under all flight conditions without screech or rumble instabilities. The following paragraphs will address various design questions aimed at providing general trend information concerning state-of-the-art augmentor design practices.

The initiation of an augmentor design involves the examination of predetermined requirements levied by the engine's mission, the airframe (system) and the flight envelope (cycles), and the recognition that some performance parameter tradeoffs will be necessary and unavoidable. The general design approach for the augmentor begins with the definition of the overall design goals of performance, weight, size, cost, reliability, durability, survivability and flight envelope conditions in a prioritized listing. Then, a more specific breakdown of these goals will reveal potential problem areas which need to be addressed. Some of these problems may include the following: combustion performance and efficiency, combustion stability (absence of rumble and screech), lean flame stabilization, dry pressure loss, burning length, mixing effectiveness, minimum temperature and pressure rise, reheat pressure loss, etc. Due to basic engine and airframe operational requirements, the augmentor designer must consider

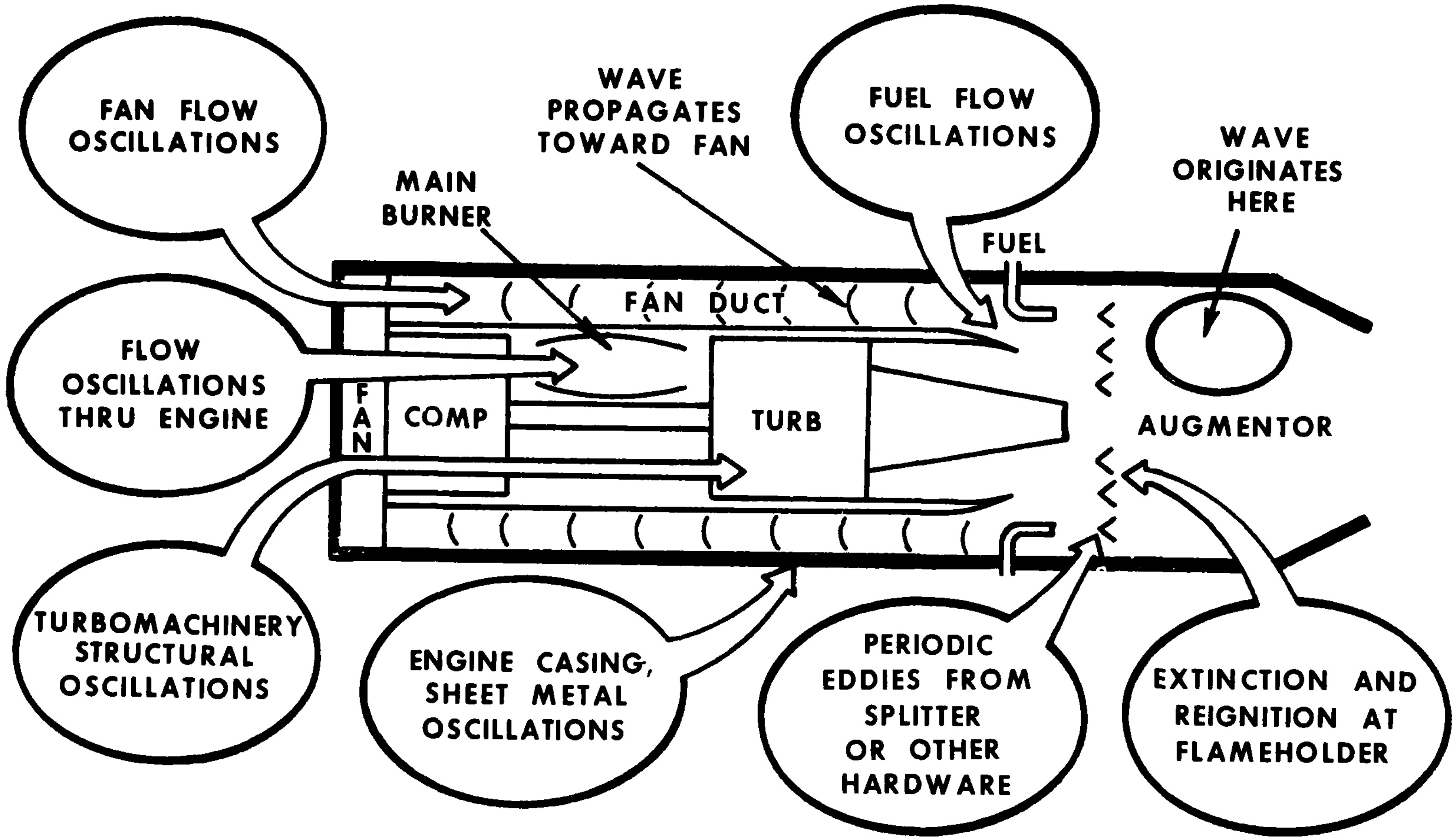

Figure 17 Augmentor Perturbation Sources

some design and performance compromises/tradeoffs in a manner least detrimental to the performance of the overall afterburning system. For example, a reduction in augmentor weight or improvement in dry performance may result in reduced component durability and reheat capability. Also, any required improvement in afterburner performance goals for a specified thrust and durability generally leads to increased cost, size and weight.

Once the design goals have been determined, aerothermal engineering development time is divided equally between analysis and experimental testing. The preliminary design process results in an augmentor size and shape for a specified level of performance. Analytical techniques used during the preliminary design include a number of augmentor design and performance prediction programs (usually computerized) covering pressure loss, efficiency, liner flow and augmentor combustion processes. The aerothermal design process establishes the size, weight and cost of the afterburner, highlighting the performance goals. Analytical methods utilized in this design phase include efficiency, cooling liner and screech liner computer programs, stability models and augmentor pressure loss calculations. Of these major analytical tools, three are empirically based (e.g., combustion efficiency, liner flow and temperature, acoustics) and two are theoretically based (e.g., augmentor stability pressure loss calculations). Therefore, it is the augmentor flowpath accompanied by performance/ design predictions which comprise the analytical design methodology for an afterburner system.

Experimental augmentor testing is conducted initially in rig systems, followed by detailed development tests on engines. The general sequence of events follows a path from simple flametunnel tests through scale model component rig to large component rig and finally full-scale engine tests. Final augmentor development, however, must ultimately be accomplished during actual engine testing where the effects of component performance, inlet distortion and duct and exhaust nozzle influences can be more accurately defined.

a. <u>Specific Augmentor Design Considerations</u>

Variations in flameholder geometry, fuel spraybars/rings and mixer geometry have direct effects on afterburner efficiency and combustion stability. Dimensional variations that affect combustion stability and fuel/air distribution by creating wakes and interfering with spraybar/ring and flameholder relationships are evaluated using engine manufacturer computer models. The interrelationships of these items are briefly discussed in the following paragraphs.

Flameholder geometry takes into account:

(1) Flameholder spacing -- generally is determined using Petrin, Longwell and Weiss correlations for conditions of 99% combustion efficiency and operating pressures not greater than 2 atmospheres.[2]

(2) Flameholder width -- has a direct effect on combustion stability and a secondary effect on combustion efficiency. Minimum width is determined from augmentor conditions at the stability design point using a design parameter generally unique to each manufacturer's augmentor design philosophy.

(3) Flameholder positioning -- assures equal and balanced airflow to each flameholder, the distribution of which is generally defined by streamline analysis. Axial locations, measured from the flameholder to the exhaust nozzle throat, are often determined by an experimentally based combustion efficiency and burning-length correlation. Radial positioning may be determined by manufacturer computer codes incorporating flameholder blockage and expected inlet distortion, the two principal parameters for calculating augmentor pressure loss.

(4) Flameholder array slope -- improves pressure loss, aids in fan/core stream mixing and diffusion and also improves flame stability.

(5) Flameholder cross-sectional shape -- influences flameholder drag-pressure loss.

(6) Flameholder blockage -- depends on the array and width of the flameholder; it is usually assigned some value greater than that determined by the Petrin, Longwell and Weiss correlations in order to maximize combustion efficiencies at all operating conditions.

Spraybar and sprayring geometries represent two dramatically different configurations for fuel distribution in state-of-the-art afterburning systems. The first design consists of radial spraybars close-coupled to radial and circumferential flameholders to create a uniform fuel distribution in the flameholder wake -- essential for good combustion efficiency and stability. The second design utilizes circumferential sprayrings with radial and circumferential flameholders, sized and spaced to provide uniform fuel distribution within pressure drop and turndown ratio limits. The sprayring configuration may be designed with fixed or variable orifice fuel metering. Maximum sprayring fuel pressure is determined by design, fuel pump capability and the required fuel turndown ratio. A quick-fill system may be required for the large diameter sprayrings to assure a fast response capability during military-to-max thrust transient operation.

Mixer geometry effectiveness is evaluated on the basis of mixing efficiency as related to a thermal profile. For a radial flameholder, there is a direct relationship between the number of mixing chutes and the combustion efficiency consistent with dry-loss limitations. Both the flameholder and the inner circumferential sprayring are immersed in the hot core stream for good flame stabilization. The width of the core mixing chute is nearly constant to allow for uniform bathing of the radial flameholder with hot core gases. Colder fan air is injected between the

flameholders to provide good combustion efficiency and stability. The exit plane of the flameholder assembly is angled to increase mixing area and to prevent cold fan air from disrupting the combustion process.

b. Conditions Affecting Augmentor Operation

Major changes in upstream flow conditions can have a detrimental effect on combustion efficiency, cause local durability problems and form wakes which trigger instabilities. Some of these potentially adverse core flow conditions are:

(1) High turbine exit Mach number

(2) Severe turbine exit swirl

(3) Basic core component design changes

(4) Hot/cold streaks

(5) Flow separation

(6) Strut wakes

In addition, adverse fan flow conditions are created by:

(1) High fan Mach numbers

(2) Liner spillage/flow

(3) Internal fan duct flow distortion due to fuel lines, accessories, structural supports, flanges, etc.

(4) Flight-induced flow distortion

Minimization or avoidance of these undesirable flow conditions must begin with a thorough understanding of the causes of each problem area in order to implement possible solutions. Current state-of-the-art solutions to some of these adverse conditions are described in the following paragraphs:

(1) For high turbine exit Mach numbers, a diffuser must be used which can reduce the flowfield Mach number to a level which will assure good combustion flame stabilization and efficiency.

(2) Turbine exit swirl can vary substantially across a flight envelope creating wakes which cause fuel/air distortion and high flameholder velocities resulting in poor combustion efficiency, flame stabilization and screech. One solution is to reduce or stabilize the swirl level entering the augmentor using de-swirl or straightening vanes.

(3) Basic core component changes, particularly those which improve core engine performance, often result in improved augmentor inlet conditions (reduced swirl and Mach number),

and often shift fan bypass to the core. On the other hand, some designers contend that major augmentor changes are still required for even the most basic engine modifications such as: pressure level increases which require more cooling/stiffening of the liner for durability; inlet airflow distribution changes which induce hot/cold streaks; turbine or fan exit temperature increases leading to potential durability problems. Again, the recommended solution to these problems is to utilize mixing devices and tailored fuel injectors to insure a uniform fuel/air distribution to the flameholder assembly.

Adverse fan flow conditions may be attenuated in the basic forced mixed flow inlet design. Hence, fan stream Mach numbers and bypass ratio changes across a flight envelope are not considered to be major problems by the forced mixed flow design advocates. Flight induced flow distortion generally results in local Mach number changes, fuel/air ratio changes and turbulence level changes leading to decreased combustion efficiency. The use of forced mixed flow design features will often mitigate the effects of this inlet distortion. Another solution calls for the determination of flow profiles for critical points in the flight envelope and then a modification of the diffuser, sprayring and flameholder to accommodate these predicted flow variations. However, this method usually results in a conservative diffuser design, controlled sprayring fuel penetration and an increased number of injection sources, ultimately penalizing performance, cost and weight factors.

At present, there are two major types of augmentor combustion flowfield instability -- screech (high frequency >250Hz) and rumble (low frequency <200Hz). The problem of screech can be easily addressed during the design phase by incorporating an appropriate acoustic damping liner. Application of available acoustic analysis techniques to the maximum extent possible include the use of the Northern Research and Engineering Corporation model refined under the Augmentor Combustion Stability Investigation Program.[3] Also, utilization of existing screech experience from in-service or demonstrator engines is extremely

valuable to the continuation of performance improvement coupled with screech elimination. The rumble solution, however, appears to be more elusive to augmentor designers. A recently completed model for predicting rumble occurrence by tailoring fuel and airflow distributions has been developed under Air Force contract.[4] This model has demonstrated the potential for utilization as a valuable analytical tool in the augmentor design phase.

The information presented in this state-of-the-art augmentor design methodology review is intended to bridge the gap of understanding between the Government and industry's procedures/problems in the design of an afterburning system. The identification of those design technology areas which require the most improvement is the first phase, leading into advanced technology systems designed in response to specified technological needs.

3. COMBUSTION MODELING

Today's design process for combustion systems of aircraft gas turbine engines is a mixture of empirical and analytical (theoretical) procedures. By far the most dominant basis of combustion systems design today is empirical data correlations. Confronted with this fact, the difficult question of "what is modeling" must be immediately addressed. Are empirical data correlations to be considered modeling, or are only "analytical formulations based on physical variables" to be considered models?

The performance maps used in designing combustion systems are empirical data correlations which have been refined enough to be applied in a general fashion. Those models which we call theoretical are, in fact, highly evolved representations of experimentally observed phenomena. Theoretical models are built upon fundamental flow variables until the theory breaks down and empirical correlating parameters or constants must be used to close the formulation.

For the purpose of this technology assessment, modeling is considered any mathematical representation of physical phenomena which is intended to be applied to a general class of problems. This definition of modeling covers the broad spectrum from the Zeldovich mechanism for NO formation to the multidimensional, viscous flow theoretical analysis.

It is important to understand the differences, advantages and disadvantages between empirical and theoretical modeling. An understanding of these differences is a crucial guiding factor in determining which types and to what extent models are employed in the design of combustion systems.

Empirical models are used throughout the design and development process. The exact points and extent of application of empirical models varies greatly throughout the industry. Empirical models are utilized to correlate some types of complex performance. The advantages of empirical models are that they can be used to first, account for unknown or not well-understood processes, and second, mask or combine detailed hardware or flowfield features thereby eliminating or reducing the need to understand these features. However, this same masking of detail also is the major disadvantage of empirical models. Because so many physical and flow characteristics can be and are lumped into the correlating patterns, it is often difficult to isolate the controlling factors. Knowing the controlling factors is the key to solving the problem in a more fundamental and universal way. A second and perhaps the most important shortcoming of empirical models is their lack of universality. The very nature which combines the physical and flowfield characteristics makes extrapolation to a new geometry or flow size very poor. It is precisely this limitation which drives the development of more universal theoretical models.

However, empirical models constitute the bulk of the engineering tools used in the design process today. Almost all of the basic configuration-describing and performance models are empirical. Analytical models are generally restricted to aerodynamics modeling in regions of simple, one-dimensional or two-dimensional parabolic flow. Potential and parabolic viscous flow models are now in common use for inlet diffuser flowfield calculation. More complex flowfields over steps, around dilution jets and so forth are coupled with empirical models to provide usable results. Empirical models cover the broad spectrum from combustion efficiency and blowout/relight performance to smoke number and fuel spray size.

The primary advantages seen for theoretical models are first their expected ability to predict well over broad ranges of flow conditions and significant changes in geometric design, and second, theoretical models can provide better insight as to the physical feature or phenomenon most affecting the solution. A better understanding of the physical mechanism of the problem contributes greatly toward its resolution and future avoidance. The disadvantages of theoretical models are that they tend to be qualitative, and quantitative only when calibrated by experiment, and their accuracy is largely controlled by the accuracy of their input data, which are also often defined only by experimental data. So, while theoretical models offer the great advantages of improved universality and physical problem identification, they are still dependent on empirical data for accuracy and calibration.

It is difficult to generalize the use patterns of empirical versus theoretical models during the design and development stages. Whether empirical or analytical models are utilized at a given step in the design and development process is largely a function of management philosophy as to which of the empirical correlations or theoretical models will provide the best possibility of a solution when faced with a difficult problem.

The typical design sequence employs modeling in three roughly distinct phases: preliminary layout, detailed design and design refinement. During preliminary layout, empirical models are utilized almost exclusively. The detailed design phase is where theoretical models are calibrated and used to bring the design to its performance goals. The design refinement phase employs highly design specific, empirical data correlations to bring to design goal levels areas of performance which fall short. Only if a problem is extremely difficult will theoretical analysis be used to provide insight to the problem.

The technology bases behind the empirical and theoretical models of today's design practice are very old. In most cases, the technology bases of the empirical models were generated in the 1950's. Even the newer two-dimensional viscous flow computer models were generated in the mid-60's. Although some areas have been continually refined, such as the addition of airblast atom-

ization models to fuel spray technology, most important datum bases, such as NACA's jet penetration/hole discharge coefficient[5] and Kline's early parametric diffuser performance[6],[7],[8] remain in use in or near their original forms. Our technological capability has long been capable of significantly improving on these data. With the possible exception of diffuser flowfield calculations, the gas turbine combustor design system has changed very little from that described in the Northern Research and Engineering Corporation books entitled, "The Design and Performance Analysis of Gas Turbine Combustion Chambers," Volumes I and II, 1964. Our capability to design advanced performance combustors has only grown by the very gradual extension of our empirical models.

4. STRUCTURAL AND MECHANICAL DESIGN

The state-of-the-art in combustor structural/mechanical design relies principally on past experience and prudent use of combustor cooling to achieve desired hardware life. In contrast to other high temperature components, the need to define combustor thermal and mechanical load distributions has only occurred within recent years. This lack of emphasis has been largely due to the fact that the combustor seldom causes a catastrophic engine failure. The procedure commonly used for achieving increased combustor durability was the utilization of more cooling air in areas which showed local distress sometimes referred to as preferential cooling. This process, although eventually solving durability problems late in the engine development phase, often caused additional performance, stability and/or relight deficiencies.

Combustor material development and strength characterization have been almost nonexistent. Past design practices have utilized available high temperature materials which have been developed and characterized for turbine airfoil application. This practice has not hindered past combustor development because of available excess cooling air and innovative cooling design concepts. It often led, however, to increased combustor weight. Recent experience has also shown that material strength properties which are generated for turbine alloys do not always apply to the combustor because the combustor environment is still not yet fully understood.

Combustor durability testing has largely been accomplished on a piggyback basis, with only cursory prediction of the anticipated type of hardware failure mode. The typical combustor durability improvement procedure has been to test it, fix it, typically by adding new cooling holes, and retest the new configuration. While this procedure develops judicious experience within individual companies, it does little toward transferring technology into the combustor scientific design system. The type of engine test cycle required to induce representative loads into a combustor to demonstrate potential field failures is not understood and cannot yet be predicted. This indicates a significant deficiency in the designing of a durable combustor, and will be untenable in the future.

5. ALTERNATIVE FUELS AND EXHAUST EMISSIONS

a. Alternative Fuels

Fuels other than JP4 and JP5 have been extensively used by many engine companies in developing gas turbine engines for industrial and marine application. These engines are often derivatives of aviation gas turbines. As such, technology developed in using non-JP fuels for industrial/marine applications is useful to the aviation gas turbine engine community. Numerous, measurable fuel properties have been identified as influential in any gas turbine engine application regardless of the source of the subject fuel.

(1) Hydrogen Content

The fuel hydrogen content is significant in that it affects the fuel pyrolysis process in a manner which results in increased rate of carbon particle formation with decreasing fuel hydrogen. Consequently, smoke emissions will tend to increase. Further, these carbon particles contribute to the luminous emissivity of the primary flame zone. This results in increased heat transfer to the liner walls and fuel nozzles and contributes to hardware durability problems as well as thermal coking of the incoming fuel on the fuel nozzle face. More efficient and uniform

fuel/air mixing (achieved commonly with an airblast fuel injector) and leaning out the primary zone are effective means of moderating the effects on the combustor of low fuel hydrogen content.

(2) Volatility

Reduced fuel volatility may cause a number of problems. Ground and altitude ignition are substantially affected by vaporization rate, as ignition requires the presence of a combustible fuel vapor/air mixture. A fuel with a slow vaporization rate would take longer to produce an ignitable mixture. During continuous combustion, slower vaporization results in shorter time within the combustor available for reaction. In operation, this may result in low combustion efficiency at idle, manifested as increased emissions of carbon monoxide and hydrocarbons. Further, it is possible that decreased volatility can result in a change to the combustion process which affects the exit pattern factor. Such a change can seriously impact turbine life and reliability.

(3) Final Boiling Point

A particular vaporization characteristic which may itself cause significant combustion system impact is the final boiling point. It is postulated that this parameter is a key fuel characteristic affecting particulate formation. In addition, the possibility of carbon deposition on airblast fuel injectors found in a number of combustion systems is expected to be strongly enhanced as final boiling point is increased.

(4) Viscosity

Fuel viscosity increases would be expected to have much the same impact as reduced volatility in that droplet size will be increased. The larger droplets require longer vaporization times resulting in similar ignition, carbon monoxide and hydrocarbon emission problems.

(5) Bound Nitrogen

Fuel bound nitrogen in any quantity above trace level causes great difficulty in trying to control NO_x emissions. The conversion rate of fuel bound nitrogen to NO_x is very efficient (40 to 75%). The lean primary zone approach to thermally produced NO_x is not sufficient in dealing with this additional complication.

Flame temperatures in the lean zone may be sufficiently low to inhibit thermal production of NO_x but are high enough to promote oxidation of the fuel nitrogen as it is released from the hydrocarbon in the presence of excess air.

(6) <u>Thermal Stability</u>

The fuel thermal stability may prove to be the most difficult problem to handle when dealing with alternative fuels. Currently, the laboratory methods for assessing the thermal oxidation properties of a fuel are of questionable value. Part of the difficulty lies in attempting to correlate laboratory test methods with the environment the fuel actually sees in use. The other side of the problem is in understanding the process of fuel breakdown and the species that can contribute to the initiation and rate of the process. Since fuels in aviation gas turbine engine applications are used as heat sinks for oil, electronics, etc., understanding thermal stability at a more fundamental level may become critical, if a major shift in the source of jet fuel is to be considered.

b. <u>Exhaust Emissions</u>

In the current aviation gas turbine engines operating with standard aviation turbine fuels, the relationships between the production of smoke and gaseous emissions and the combustion environment are qualitatively understood. Among the five engine companies interviewed regarding the extent of understanding the effort devoted to quantifying the knowledge and the accumulated test experience in this area differed widely. The following remarks summarize the combination of the knowledge.

(1) <u>Carbon Monoxide and Hydrocarbons</u>

Carbon monoxide (CO) and unburned hydrocarbons (UHC) are typically products of low power combustion efficiency (CO is limited at all temperatures of interest due to equilibrium with CO_2). These species are formed as intermediates in the normal pyrolysis-oxidation processes of combustion and are exhausted as pollutants when their normal oxidation process is disrupted. This quenching can occur at several points in the combustion process. It is typified by insufficient time at high temperature.

Specifically, operation at lean primary zone equivalence ratios coupled with low inlet air temperatures (conditions often occurring at the idle point) and contact of the CO and UHC with incoming film cooling air are largely responsible for CO and UHC exiting the combustor as pollutants. Contributing factors to this problem are insufficient atomization of the liquid fuel (adding to the time required for vaporization), and mismatching of fuel spray cone angle with the recirculation zone (resulting in penetration of the unoxidized fuel through the primary zone).

(2) Oxides of Nitrogen

Oxides of nitrogen (NO_x) are products of high power combustion. In combustion with standard aviation fuels, containing only trace quantities of fuel bound nitrogen, the source of NO (the primary oxide of nitrogen in the exhaust) is the reaction of molecular nitrogen contained in the air with the oxygen also present. High temperature, available oxygen, and long residence time in the combustion environment favor high NO_x production.

(3) Carbon Particulates

Production of carbon particulates exiting the engine most noticeably as visible smoke is also a product of high power operation. Its chemistry of formation and oxidation is less well understood than that of the gaseous emissions. However, qualitatively it is formed in the primary zone in regions of high fuel/air ratios, resulting from poor fuel atomization and poor fuel/air mixing, and its rate of formation increases with pressure.

In conclusion, the area of alternative fuels as applied to aircraft turbopropulsion systems is now undergoing intensive study. The detrimental impact many of these fuels may have on combustion system performance and exhaust emissions have been highlighted above. Both fuel property characterization and emission studies are now underway in an effort to scope the degree or severity of the problems which may arise as a result of shifting to alternative fuel sources having much relaxed specifications.

SECTION III
ADVANCED TECHNOLOGY TRENDS

The evolution of technology in the turbopropulsion combustion field reflects a wide range of technical advancements and design innovations. This chapter shall serve to summarize many of these technological trends spanning a period of twenty-to-thirty years and ultimately projecting a number of years into the future. These projections provide much of the basis for the technology needs identified in Chapter IV and lay some of the ground work for specific research activities identified in the subsequent long-range Technology Plan of Chapter V. As in the previous chapter, each of five principal areas of interest is reviewed.

1. MAIN BURNERS

Eight advanced engines were used to develop advanced technology trends for main burners. Clearly, these sparse data do not alone indicate trends, and therefore, they must be supplemented by other related efforts, much of which is derived from on-going exploratory development activities. Also, technology advancements are, in the long run, driven by perceived needs. Trends noted in this section are, thus, influenced by known technology needs and projected weapon system requirements.

a. Combustor Liner

Engine cycle pressure ratios will continue to rise and will reach levels in the upper thirties to low forties in the next ten-to-fifteen years. Some engine designs having pressure ratios in the forties have been proposed, but these operate at a lower pressure ratio at sea level. When compared to a 25:1 pressure ratio engine, the cooling air temperature for a 37:1 pressure ratio cycle is increased by approximately 175°F to 200°F; yet, liner cooling air requirements are still within the range of practicability.

This trend of increased cycle pressure ratio continues to reduce the combustor flow parameter of future engines. As a result, a turbofan engine of low-to-moderate bypass ratio could be built with a 37:1 pressure ratio for a 15,000 lb. thrust

class with a combustor flow parameter of approximately 5-6. For engines of this class, very small, high heat release combustors are required. Liner specific weight and liner specific cooling airflow generally become less significant because liner area is small. Hence, multiwall liners having specific weights of more than 10 lbm/ft^2 and effectively utilizing cooling air fluxes of up to 0.04 $lbm/sec\text{-}in^2$ are practical. For example, liners of this type can be considered using today's materials with no increase in metal temperature, but with BOT's in excess of 2800°F.

Fuel impingement can be a problem with combustors of small dome height. This results in coking, hot streaking, liner burnthrough, poor pattern factor and exit temperature profile, low combustion efficiency and increased chemical emissions. As a result, there is increased activity in combustor front-end fuel (and air) management (See also Section III-5). Also, since advanced liners require less cooling air per unit area, the hot-side air film is not as effective in repelling fuel impingement. However, when advanced liners are used for high temperature rise combustor applications, the primary zone cooling air flux may be greater than its low BΔT, film-cooled counterpart.

Advanced liner designs for BOT applications above 2800°F typically are of the double wall or multiwall construction. (Some "interim designs" essentially take existing film-cooled liners and add an impingement plate.) However, it is becoming generally recognized that long-life liner designs for high temperature applications must either thermally and mechanically isolate the hot inner liner from the cold outer support structure or provide minimal thermal gradients across the liner wall. An example, is the advanced, double wall design or "shingle combustor" (Figure 18) developed by the General Electric Company under an early Navy V/STOL component development program. Other engine manufacturers are also working to develop liners of this same general construction. The shingle or segmented liners exhibit a specific weight of more than 10 lbm/ft^2 and can effectively utilize up to about 0.05 $lb/sec\text{-}in^2$ of cooling air. Fortunately, these advanced liner designs require average cooling air fluxes

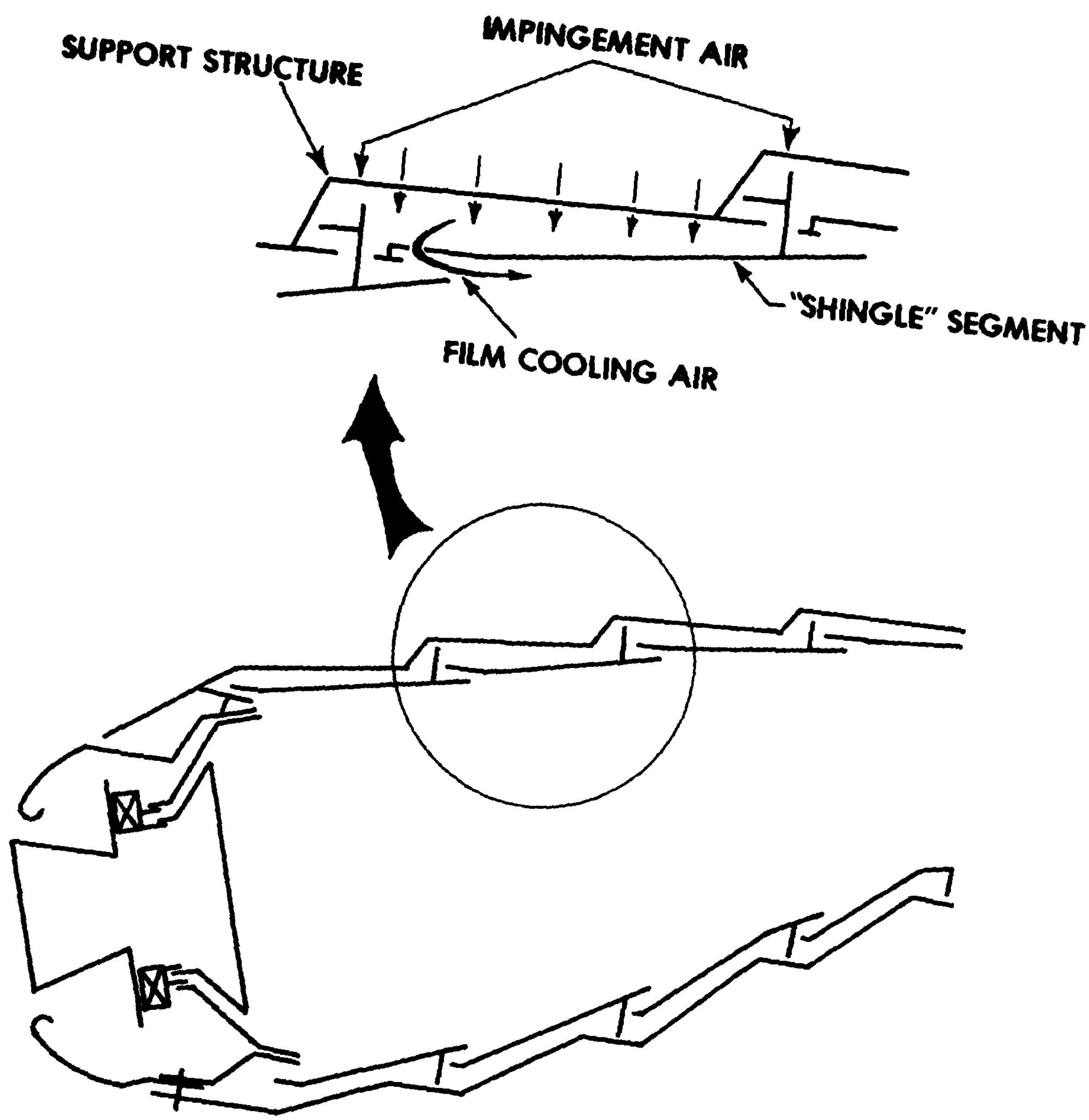

Figure 18 "Shingle" Double-Wall Combustor

of only 1/3 to 1/2 of this value in order to meet design metal temperature limits. An alternative to the double-wall liner is to minimize thermal gradients across the liner wall by using transpiration-cooled materials or by applying protective thermal coatings to the liner material. Detroit Diesel Allison is aggressively pursuing a simulated transpiring material development for combustor application called Lamilloy ^{R}. The Lamilloy ^{R} materials, if successful, approximate a lightweight, reinforced sheet metal construction but with cooling flows equal to or less than those required of double wall designs.

b. Fuel Injection

Airblast fuel injection is expected to be the principal fuel/air preparation technique for future engine designs. Premix fuel injection will most likely be unnecessary unless further emissions reduction from aircraft engines becomes necessary (see Section III-5). It must be shown, however, that premix fuel injection systems can be reliably used without problems of flame stabilization, flashback or undue premix length before they will find application.

With high BΔT combustors, front-end stoichiometry and its variation in off-design operation become important due to the inherent problems of altitude relight, lean blowout upon deceleration and associated problems of starting and combustion efficiency. These problems can be solved through controlled redistribution of air within the front-end primary holes and dilution holes, i.e., through variable geometry. In the future, virtually all engine manufacturers will be considering variable geometry, variable minimum fuel flow rates, staged combustion and variable spray angle fuel injection in order to better control the problems cited above.

c. Inlet Diffuser

Combustor inlet diffusers operating behind axial compressors typically receive air at approximately 0.3 Mach number. The flowfield is then diffused to approximately 0.1 Mach number for combustion and for feeding the inner and outer liner annuli.

Over the past several years, it has been continuously pointed out that the axial compressor can operate more efficiently and require fewer stages if the exit velocity field can be increased to Mach numbers of 0.45 or higher. Because of these associated compressor benefits, diffuser inlet Mach numbers for future engines are expected to become higher. It is likely that diffuser Mach numbers will increase to a level necessary to reduce the number of compressor stages by at least one or two. This will depend, of course, on the success of diffuser development efforts in effectively accepting higher inlet Mach numbers without excessive increases in combustion system pressure loss. In recent years, this challenge has been accepted resulting in two high Mach number design approaches: the Swirl Combustor developed by Pratt & Whitney Aircraft[9] and the Vortex Controlled Diffuser (VCD) for the Detroit Diesel Allison developed High Mach Combustor.[10] Both designs were successful, but each exhibited certain practical limitations relative to near-term development or production engine incorporation.

(1) The swirl combustion system (Figure 19) is mechanically complex and may not enter production because of inherent life cycle cost and basic considerations, of repairability, reliability and maintainability. Its short length and performance, however, were found to be good, and its premix and swirl technology may yet find application in other combustors.

(2) The VCD (Figure 20) a boundary-layer bleed design, realized low pressure loss even when the vortex bleed flow was reduced to zero; however, its best operation occurred when positive bleed was provided. Bleed air, of course, can represent a loss to the cycle and brings on the added complexity of bleed values and plumbing.

Based on these projected technology trends, a number of perceived needs can be derived. Many of these needs are summarized in Section IV-1.

2. AUGMENTORS

New augmentor technology replaces the old as a function of added engine requirements/capability and sustained improvement in

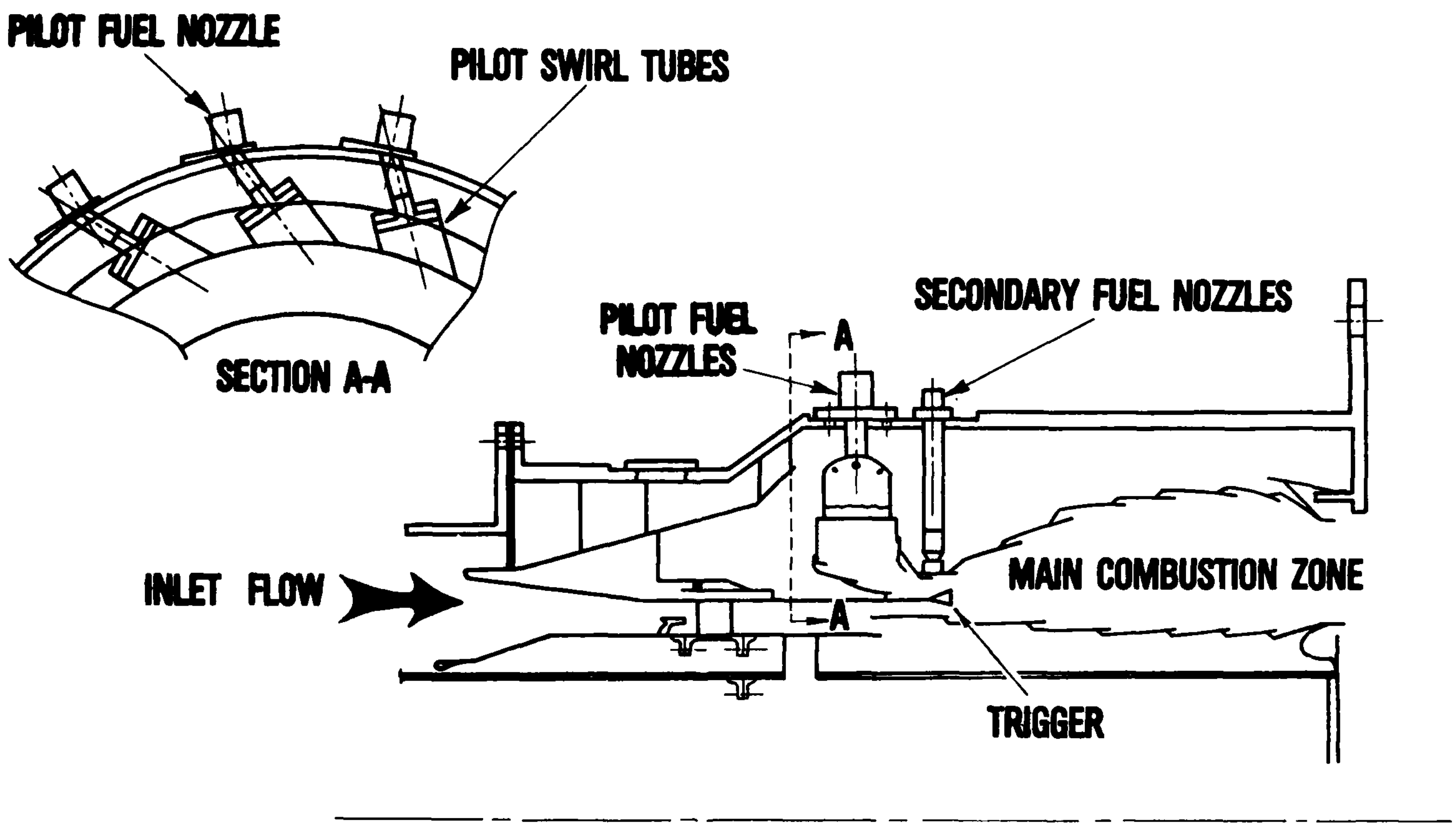

Figure 19 Swirl Combustion System

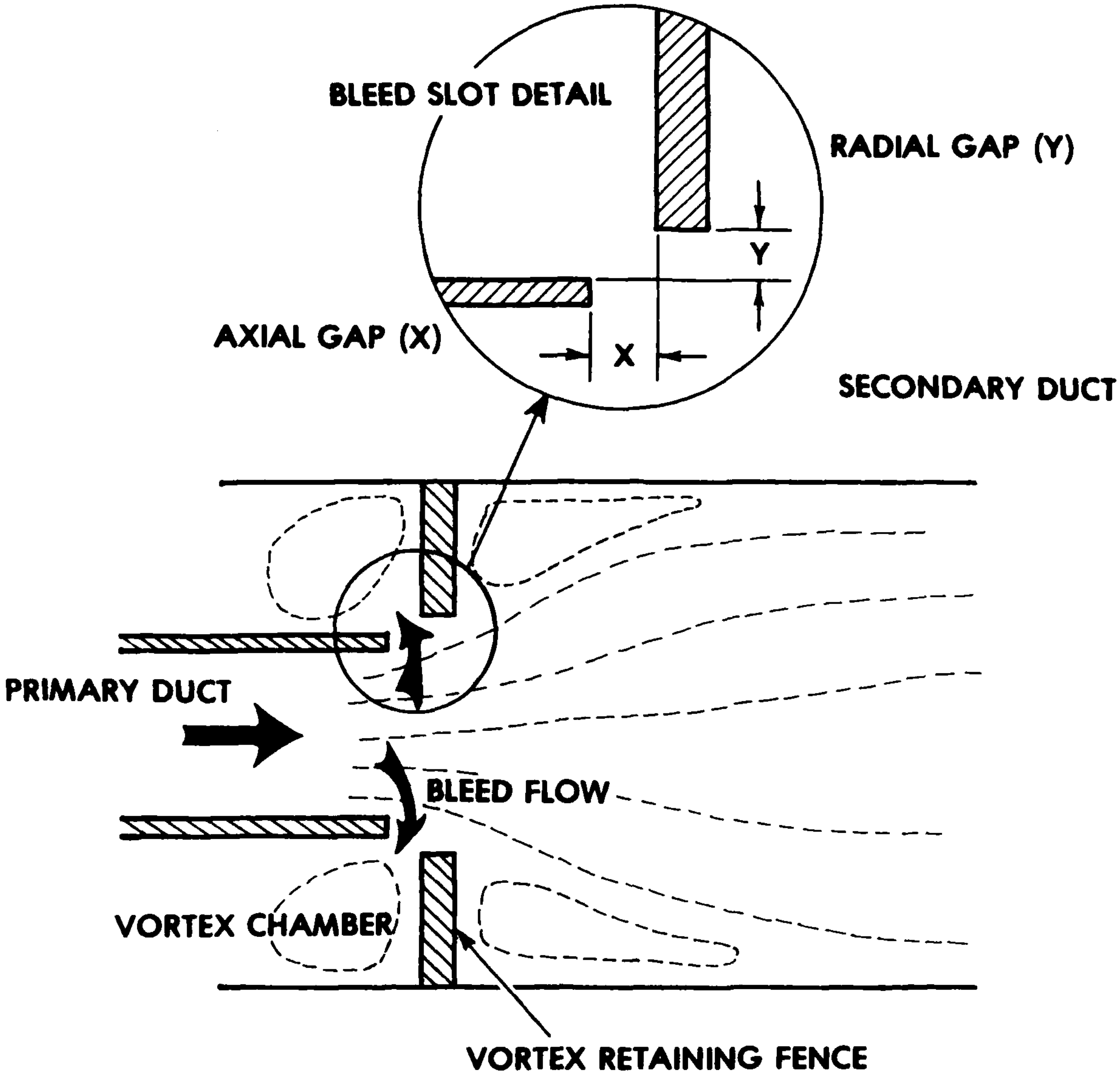

Figure 20 Vortex-Controlled Diffuser

augmentor performance as well as designer originality. During the past ten years, the augmentor geometry, combustion stability and performance have experienced the most significant technological changes. In the same time frame, overall combustion efficiency of afterburning systems with nozzle and liner cooling air taken into consideration has maintained a relatively constant level of 85 to 90%. This efficiency is not expected to dramatically increase until technology for improved liner and exhaust nozzle cooling techniques, more durable materials and better fuel/air mixing have become available.

The augmentor has taken on a relatively new look with the recent trend to reduce the radial flameholder width from 1.5" to 1.25". This change has considerably improved dry pressure loss. In addition, mixing chutes, which proved to be successful in high bypass ratio turbofan augmentors, have been introduced into afterburners with a low bypass ratio to induce flamespreading into the cold fan stream. Variable-geometry features (flameholders, mixers, etc.) are also being considered for future augmentors to minimize dry pressure loss during nonaugmented operation. The length-to-diameter ratio, L/D, has not changed significantly over the years because of its minimal effect on overall engine weight. However, this parameter will be investigated more thoroughly with the advanced full swirl augmentor and VORBIX systems (an acronym for Vortex Burning and Mixing). The benefits of these designs will be discussed later.

A great surge in research effort studied the problems surrounding improved combustion stability in gas turbine engine augmentors. As pressures and temperatures rose in advanced technology engines, high frequency pressure oscillations, known today as screech, plagued afterburners. Engine manufacturers found that cooling liners in the augmentor could be altered by tuning the cooling holes and backing volume (behind the liner) to dampen the screech. Tuned liners have eliminated most of the screech problems in augmentors today, although occasionally isolated incidents of high frequency combustion instability still occur. Some interest in this stability problem remains for three

reasons: 1) although most screech problems have been solved, screech still exists and is not completely understood, 2) some relatively low frequency screech has occurred that cannot be easily handled by cooling liners, and 3) the potential problems with the future use of very high temperature augmentors may worsen the screech problem.

The low frequency combustion instability known as rumble is the most serious of the combustion instabilities experienced to date. Recent research has been very successful in providing a better understanding of the phenomena and mechanisms contributing to the onset of rumble. The analytical model developed recently at Pratt & Whitney Aircraft under Air Force/Navy sponsorship is effective in analyzing the rumble potential of turbofan augmentors when geometry, augmentor type and operating conditions are given.[4] This model should be useful for future engine designs. Unfortunately, the results of the rumble research only verified the complexity of the rumble phenomenon and its avoidance. The interaction of spraybar/ring and flameholders through lengths, widths and spray conditions envelop the augmentor designer in a maze of design and performance variables and combinations thereof. The rumble computer model is expected to aid engine augmentor designers in their search for an improved rumble-free geometry configuration.

Though the V-gutter flameholder configuration remains the mainstay in augmentor technology, two swirl concepts are being researched. One of these new schemes is the VORBIX concept (Figure 21) which utilizes a large number of swirlers or triangular (delta-wing) vortex generators to produce high levels of turbulent mixing with small-scale vortices.[11] The VORBIX system requires a pilot burner. A full engine performance evaluation has not yet been completed. An alternate concept is the full swirl design (Figure 22) in which the entire augmentor flowfield becomes a single vortex.[12] The full swirl augmentor uses buoyancy caused by the difference in outer and inner temperature fields as its principle of operation. The swirling flow sets up centrifugal fields which allow the hot outer gas (created by an annular pilot burner) to be displaced toward the center while the colder, more

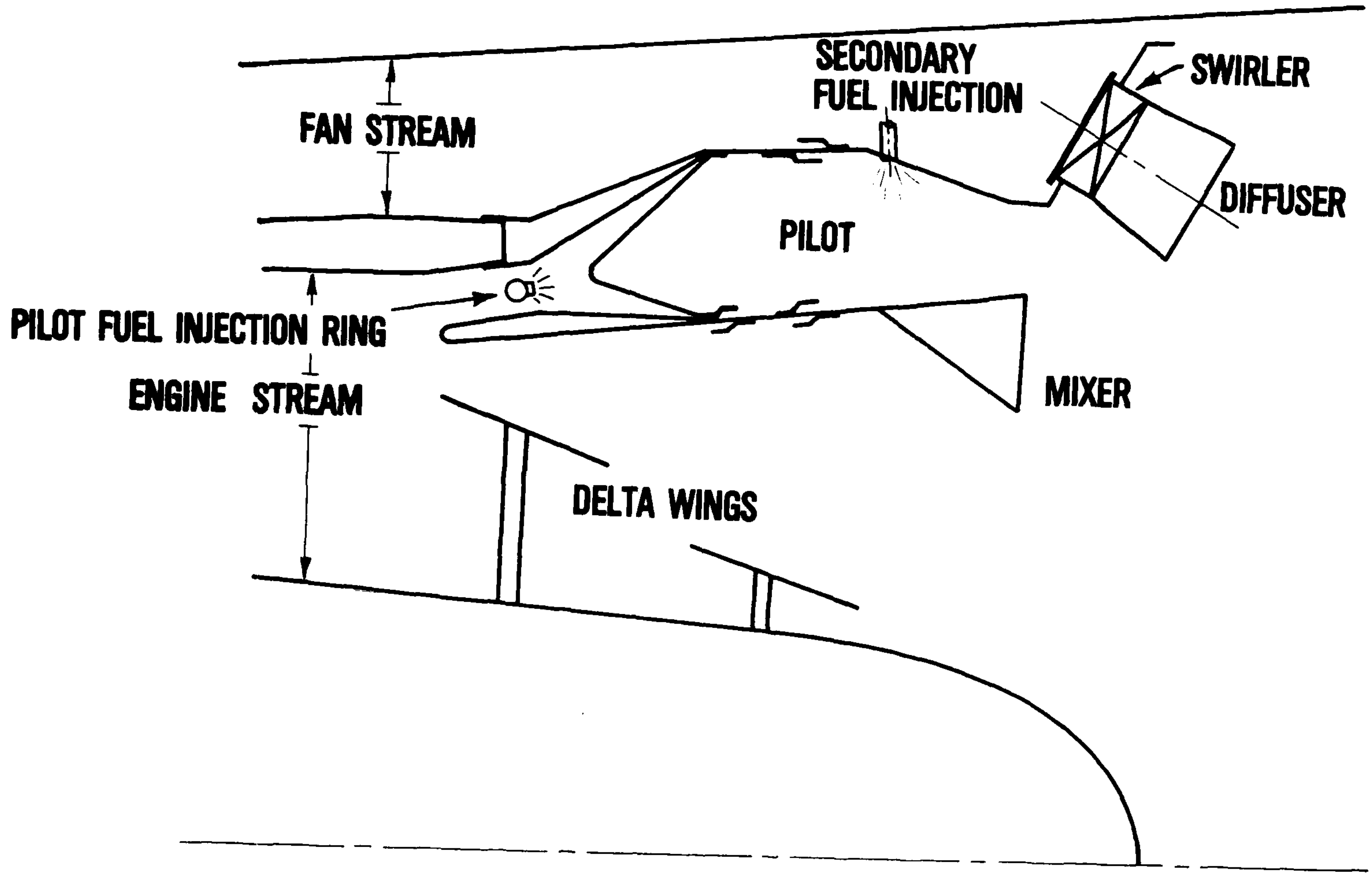

Figure 21 VORBIX Augmentor

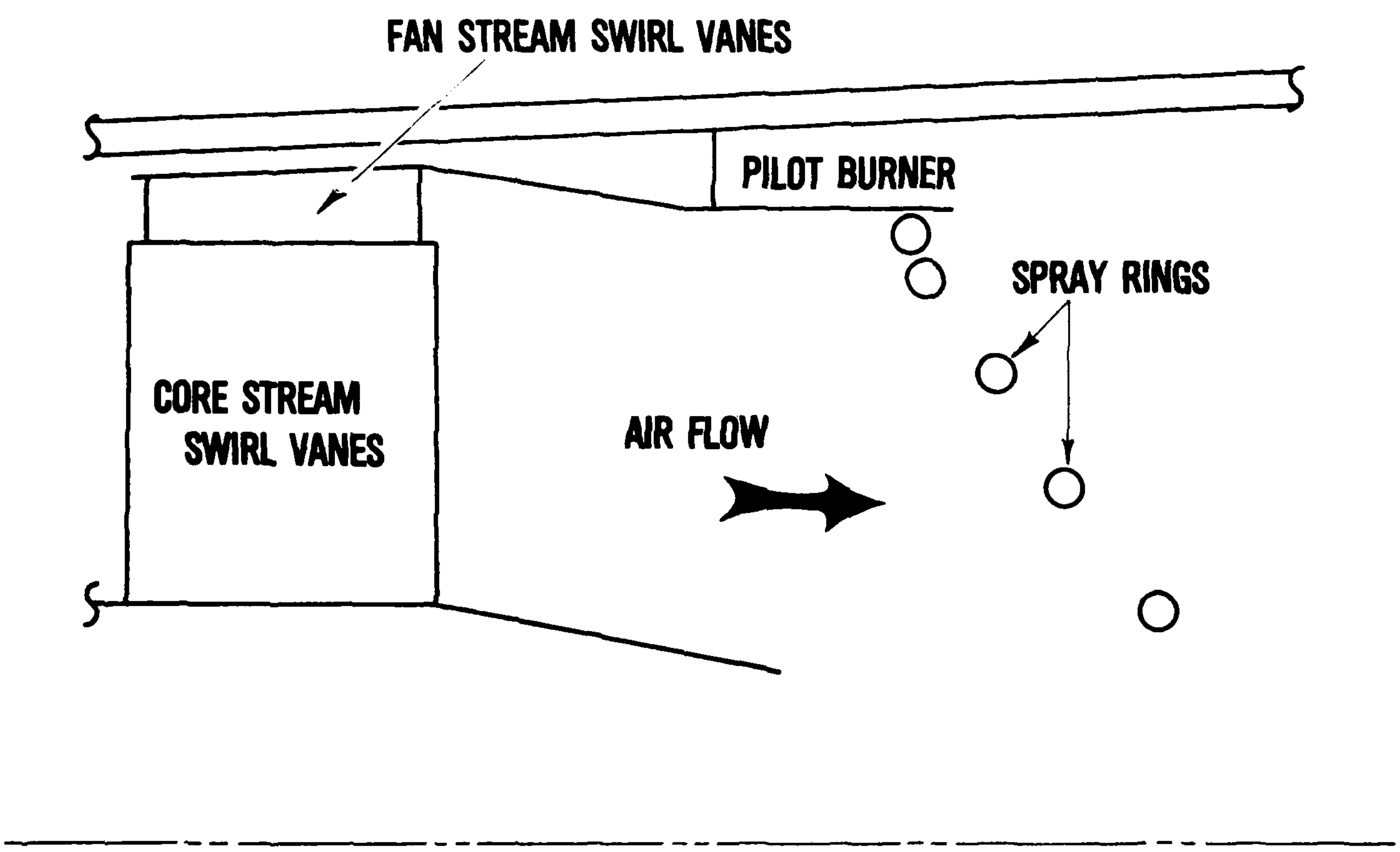

Figure 22 Full Swirl Augmentor

dense gas is centrifuged through the hot gases, to the outside. Consequently, more effective flamespreading as well as improved mixing of the flow is accomplished. Both the full-swirl and the VORBIX techniques show little residual swirl at the nozzle and are expected to display higher efficiencies in a shorter length when compared to the conventional afterburner.

As the trends have indicated, advanced engine augmentor systems will require technology improvements in the areas of fuel injection, mixing, stability, durability and piloting to meet the demands of future USAF aircraft. New programs that address some of these needed technology modifications will be discussed in later sections of this report.

3. COMBUSTION MODELING

Combustor modeling or just "modeling" has come to mean "computer" to most engineers. Indeed, most if not all companies have automated their design systems to some degree. This automation of design information can provide more rapid design layout and faster and more detailed parametric investigations. Yet, computer analyses have some pitfalls awaiting the unwary such as different versions of a code yielding different answers to the same problem, time wasted in parametric studies which would not have been necessary had the designer been familiar with the equations he was solving, or simply relying on old data because the new were never incorporated.

Computer automation is the trend of the future. Described in its lowest, most fundamental terms, computer automation allows the increase in the allowable number of computations which can be applied to a given problem. The increasing computing power allows even more complex theories to be applied to solving problems.

The most advanced modeling area is that of structures. Almost all of the companies have good capability to use large three-dimensional elastic structures codes such as NASTRAN. These codes have been in existence for a long time and are still continually being improved. New capabilities which are the main focus of current work are in the areas of failure analysis and plastic stress calculations. Failure analysis has become a very

important part of all development programs. Life cycle costing analysis is focusing attention of the life and maintenance/repair costs of new hardware. New engine health/history monitoring systems should help provide the vital link between field-observed failure, engine use history and the design process. Current theoretical efforts lie in the areas of elastic theory approximation of plastic phenomena and plastic structural behavior theory. The plastic behavior theory is a far-term payoff effort.

Heat transfer is the weakest of the modeling areas and the area in which the least is being accomplished or even pursued. Very little effort is being expended to improve either the convection or radiation theories. In practice, radiation continues to be initially estimated empirically, and in detailed design, accounted for by experimental calibrations. One of the biggest problems holding back convective heat transfer theory development is a need for better aerodynamics theory.

Aerodynamics is the technology receiving the greatest attention today. Two- and three-dimensional elliptic flow codes are operational in some of the engine companies and are being utilized to aid the design and problem solution efforts at those companies. Because of the great complexity of the airflow system in a gas turbine combustor, these codes are being utilized to visualize the combustion system flowfields in a multi-dimensional, semi-quantitative manner, heretofore, an impossible task. The contribution that these codes provide in problem solving and design improvement will continue to drive their development. Design system versions are now under development. Research efforts to improve these aerodynamic codes are concentrated in the area of turbulence modeling.

Chemical kinetics modeling is receiving a great deal of attention. The calculation of hydrocarbon fuel/air reactions is very important to combustion system modeling. Reaction kinetics impact efficiency calculations, species concentrations for emissions prediction and heat release for temperature rise, mixing and heat transfer calculations. Important questions being researched are: 1) what are the important reactions in the combustion of hydrocarbon fuels, 2) what are the appropriate reaction rates under varying

degrees of turbulence and at different temperatures, and 3) what are the radiation characteristics? Currently, reaction kinetics are modeled in two basic ways. First, simple mechanisms are coupled with the fundamental aerodynamic equations, and second, detailed mechanisms are used in a network of stirred reactors. Species concentration calculations in both formulations have generally not exhibited good agreement. Some work is being conducted to establish global reaction rates for hydrocarbons which would improve overall effectiveness for heat release and end product computations in both types of models.

Fuel droplet formation, trajectory, vaporization and vapor mixing/diffusion are areas where a great deal of research is being conducted. The model development in this area is predominantly empirical due to the complex phenomena which must be accounted for in relatively simple fashion. The investigations in these areas, when combined with the advanced aerodynamics, contribute significantly to our capability to predict fuel distribution, mixing, regions of high heat release, heat transfer and emissions. The treatment of the fuel spray in a gas turbine combustor is very important.

Finally, the basic numerical structure, by which the calculations of most of the above work are accomplished, is being explored. Both finite difference and finite element numerical schemes are being examined for their possible advantages. To date, there are no overwhelming advantages of one system compared to the other. As a result, the better established approach (i.e., difference techniques) is receiving the greatest attention. Current work is attempting to identify differencing techniques with low growth rates in the required number of computations versus the number of nodal points employed and the number of equations solved. Research is underway to identify higher order accuracy differencing schemes, improved stability (allowing larger time steps) and more open grid spacing where possible (i.e., higher cell Reynolds numbers). Higher order accuracy and improved stability will contribute significantly to increasing computational speed and accuracy.

The automation of design information is the trend which is moving throughout the aircraft gas turbine industry. This trend of computerization brings with it a movement toward the application of more sophisticated theoretical models or the combination of existing models into a more unified and optimized mode. The research which supports this transition is primarily theoretical, but is significantly augmented with important empirically based work. The principle broad classifications under which this supporting research is being conducted are aerodynamics, chemical (hydrocarbon) kinetics, stress analysis, fuel spray, numerical analysis and heat transfer. In support of each of these areas there is a great deal of needed research.

4. STRUCTURAL AND MECHANICAL DESIGN

Combustor mechanical/structural/life design is becoming increasingly difficult because of higher cycle temperatures and an attendant reduction of available cooling air. The achievement of current design lives at the more severe operating conditions will require a greater understanding of combustor mechanical and thermal loads and the type of failure modes these loads induce in the combustor. This understanding must be determined by utilizing scientific principles, not just extensive experience.

Sophisticated analytical stress/life prediction procedures are in their infancy (e.g., finite element, plasticity, creep relaxation, etc.), and have seen very limited use in combustor design. These capabilities must be streamlined, limitations identified and accuracy defined for specific operating regions before they can be widely used in the gas turbine industry. This design/analytical model development and verification cannot be accomplished just by industry because of the size and complexity of the effort. Consequently, a combined government/industry effort has been initiated to begin development of the essential models and analytical tools for combustor life prediction, stress analysis and heat transfer. Much of this preliminary effort will first draw upon analytical procedures developed for turbine hot-section components to identify existing model limitations and

capabilities when applied to the combustion system. Development of appropriate structural and mechanical design tools will assure achievement of future high temperature, long-life combustion systems.

5. ALTERNATIVE FUELS AND EXHAUST EMISSIONS

Fuel injection and combustor technology are currently being developed that will be of use in mitigating problems of emissions as well as reducing the impact on the system of alternative fuel utilization. Air assist and airblast fuel injection are being used more widely in aircraft gas turbines. Long-term goals in fuel injection center about premixed/prevaporized systems. For advanced combustor designs, double annular and staged systems have already been demonstrated. For far-term application variable geometry techniques are being investigated.

a. Alternative Fuels

The trend toward increased control over the local combustion process is in itself beneficial to creating fuel flexible combustion systems. Airblast atomizers have demonstrated the ability to satisfactorily atomize fuel of high viscosity (diesel and high density missile fuels).

Maintaining a locally lean primary zone has been shown to favor low particulate generation, and thus, provide a low luminous emissivity. This aids in reducing the impact of a low hydrogen content fuel on smoke emission and liner temperature. In general, the more control developed over the combustion process (and fuel injection process) the less impact a change in fuel type is likely to have. This is the trend in combustion/fuel injection technology.

Control of the conversion of fuel bound nitrogen to NO_x may be important in handling fuels derived from certain nonpetroleum sources. One technique examined by several companies is a rich burning primary zone concept. This design requires the primary zone to be well-mixed and to operate at an overall rich equivalence ratio. The local lack of O_2 inhibits the formation of NO_x as nitrogen is released from the fuel. At the same time, local

temperatures can be kept low (as in lean operation) inhibiting thermal NO_x formation. However, since the combustor still operates at an overall lean fuel/air ratio, it is necessary to bring the rich primary zone mixture down to the lean exit fuel/air ratio. This rich-to-lean transition requires an amount of time at an equivalence ratio of one, a condition detrimental to low NO_x. However, if this transition from rich to lean is made rapidly, total NO_x production can be minimized. This technique has been successfully demonstrated. Note that, as before, the concept calls for continual control of the combustor stoichiometry.

b. Exhaust Emissions

In controlling gaseous emissions and smoke the trend in technology is to maintain control of local stoichiometry in the combustor over the entire range of the system. Advanced fuel injection techniques have seen the most common initial usage. Airblast (and to a lesser extent, air assist) fuel injection has demonstrated the capability for reducing local variations in fuel/air ratio throughout the primary zone. This has proven to be beneficial at high power operation in reducing smoke and thermal NO_x production. In a simple, fixed geometry system this improvement at high power is often at the expense of low power emissions (CO and HC) as well as the ignition capability of and flame stabilization in the combustors.

Performance goals at high and low power are often in conflict because of the wide range of operating conditions over which an aircraft combustion system must perform. The double annular combustor concept has been developed as one means of dealing with this problem. This technique calls for two, separately fueled, combustion primary zones (typically radially stacked) to feed common secondary and dilution sections. One primary zone is optimized for low power operation. It is designed to operate fuel rich and at low overall air flows. Thus, it provides for good ignition, flame stabilization and low power emissions while having minimal effect on high power operation. The second primary zone is optimized for the high power setting. It operates at lean fuel/air ratios and handles most of the engine fuel flow, providing for low smoke and minimal thermal NO_x.

Staged combustion is another technique to separate low and high power operations, while optimizing each. The combustor maintains its traditional simplicity while the fuel delivery system is altered. The system may be optimized for cruise operation. At a lower power setting only certain fuel nozzles are fueled. This creates locally high fuel/air ratios providing good ignition and low power stabilization features. At the same time, locally high temperatures reduce low power emissions.

More extensive control of combustor stoichiometry can be accomplished with variable geometry techniques. This process, just beginning development, provides a means to continuously control local conditions in the combustor over its entire operating range. Thus, the system is everywhere optimized.

Drawing from these projected trends, a number of technology needs were identified. Some of the more important needs are highlighted in the following chapter under Section IV-5.

SECTION IV
TECHNOLOGY NEEDS

This section is obviously an outgrowth of the previous section on Technology Trends. As one might expect, most technical needs for future research are based on either known problems associated with today's systems or problems anticipated with systems to be developed over the next several years. Each principal area of interest under this assessment is again addressed separately highlighting many of the technical needs/deficiencies the various engine company participants recommended for further research and development. From this section, specific programs were defined leading to the prioritized list of research activities and subsequent long-range technology plan of Section V.

1. MAIN BURNERS

More emphasis is being placed today on life, durability, repairability and other Life Cycle Cost (LCC) factors. This does not mean that performance driven factors, such as increased turbine inlet temperature and compressor pressure ratio, will lose importance. Instead, the technology advancements (such as better liner cooling) driven in the past by improved performance will now be driven by LCC factors. For example, an engine designed to operate at a BOT of 3000°F could be derated to 2800°F, potentially doubling hot-section life. Nevertheless, there will be a continuing effort to demonstrate higher and higher BOT in advanced combustor designs while exploiting advancements in cooling technology and new materials to assure acceptable life and hot parts reliability.

The following needs consider both performance and durability goals. Performance goals can be separated into the following basic areas:

1) Burner outlet temperature
2) Combustion efficiency
3) Combustor system pressure loss
4) Combustor system length (affects turbine and compressor efficiencies)
5) Diffuser inlet Mach number (affects compressor efficiency)

Also, performance can be considered from an operational point of view:

6) Starting (altitude relight and ground starting)
7) Idle combustion efficiency
8) Low speed stability

Life cycle costs are affected by performance, but also by additional factors related to combustor-engine compatibility, reliability and maintainability:

9) Pattern factor (turbine vane life)
10) Hot streaking (liner life & turbine vane life)
11) Combustor exit temperature profile (turbine blade life)
12) Combustor system life
13) Combustor system weight (also affects aircraft performance)
14) Combustor system acquisition costs
15) Repair costs
16) Unit fuel cost (affects the relative importance of all other costs)
17) Ability to use alternative fuels

Every combustor development program addresses one or more of these 17 factors except for regulated efforts like flight safety and environmental concerns. Each of the technology needs discussed below addresses one or more of these factors.

It is likely that the next advancement in fighter engine performance will necessitate a BOT of 2800°F to 3000°F. Such an engine could go into production as early as 1990. Hence, combustor system technology advancements in several areas are needed to meet mandatory life requirements and performance goals.

a. Combustor Liner

The field life of current fighter engine combustor liners is typically 750 hours or less. Due to ever-increasing maintenance and repair costs, there is a firm need to at least double this life, and in some cases, to increase hot-section life to as much as 3000 hours with repair. For fighter engines there are approximately 1.25-1.50 equivalent thermal cycles per flight hour. Therefore, the liner must survive up to 2250 cycles without

repair or up to 4500 cycles with repair. Since it is likely that a fighter engine will go through overhaul at 1500 hours (for reasons other than just the combustor), a combustor liner that can survive 1500 hours, be repaired and then be returned to the fleet for an additional 1500 hours of service can provide a dramatic impact on propulsion system life cycle cost.

There is a long-term need to improve combustor liner materials. The primary criterion is to increase maximum metal operating temperature capability because of its favorable impact on cooling air requirements. It is also important to note, however, that the hot spot limiting metal temperature of any liner could be substantially increased, if existing thermal stresses could be relieved (as with segmented liners). This, in turn, would allow for incorporation of advanced high temperature, moderate strength, oxidation resistant alloys permitting even higher metal temperature capabilities.

Liner operating temperatures can also be reduced by application of thermal barrier coatings to the exposed metal parts. These coatings are intended to provide both insulating and oxidation protection. Before thermal barrier coatings can be considered practical, however, it must be shown that the liner geometry will permit coating of all of the required hot-side exposed surfaces. Also, it must be shown that the coating will remain attached for a significant portion of the liner life.

The exit temperature uniformity (pattern factor) of today's production engine combustors is not good. Most field engines exhibit hot-section distress of one form or another due to high pattern factor and hot streak problems from the combustor. There is a need, therefore, to reduce burner pattern factor to reasonable levels consistent with hot-section life requirements and to determine the causes of high pattern factor and pattern factor deterioriatization with engine usage. This, of course, requires a basic understanding of combustor flowfield aerodynamics, turbulence and fuel/air mixing in the dome or primary zone of the combustion system.

In the area of off-design performance of advanced high temperature rise combustors, there appears to be no known way to

effectively deal with combustor front-end stoichiometry variations during rapid throttle transients without resorting to some form of variable-geometry. The principal problems relate to altitude starting, ground starting, "snap-decel" throttling from high power and low speed instability, including emissions and combustion efficiency. The questions, yet to be resolved, deal with the practicability of controlling front-end stoichiometry by: 1) varying fuel flow or fuel distribution using fuel staging or variable fuel spray angle techniques, 2) front-end airflow variation using variable-geometry on the dome, or 3) liner airflow variation using variable geometry on the liner.

b. Fuel Injection

There are numerous instances in production engines which indicate that fuel impingement and fuel/air distribution can result in serious durability problems. With small, compact combustors having dome heights of three inches or less as well as some of the advanced, high temperature rise combustors now under consideration, this could be even more pronounced. Hence, the need for improvements in fuel injection system design has been defined and must now be an integral part of the combustor design methodology.

c. Inlet Diffuser

The major objective of the combustor inlet diffusion system is to provide low total pressure loss and high recovery in a short length. New engine cycle studies have indicated definite design and performance advantages by increasing through-flow velocities. Higher through-flow velocities or Mach numbers, however, place increased importance upon diffuser performance. To obtain the best payoff from high through-flow technology diffuser recovery, losses and length must be held to current levels or reduced. In addition, high through flow technology will require efficient, effective and stable diffuser performance over a very wide range of inlet Mach numbers.

The vortex-controlled diffuser is a separated flow diffuser which has shown great promise of meeting the needs of high through-flow technology. Efforts to fully develop vortex-controlled diffusion systems need to be continued.

An important part of combustor inlet diffusion is the interaction effects between the diffuser and the combustor dome. This interaction can play a significant role in the airflow distribution and its sensitivity to off-design conditions. The interaction between diffuser and combustor performance must be accounted for, especially in the application of advanced separated, contoured wall or active control diffusion systems.

To provide the short length, high performance diffusion systems needed by advanced cycle engines, significant advances must be made in our understanding and ability to analyze separated flow, curve-boundary, body-influenced and actively controlled diffuser flowfield aerodynamics. In addition, the development of an understanding of combustor-diffuser interaction effects must be an integral part of the design methodology used for future turbopropulsion combustion systems.

2. AUGMENTORS

The purpose of identifying technology needs is to provide an avenue for the programming of future technology development efforts. The technologies discussed here represent ideas for problem solving in areas which have the greatest expectations for improvement of augmentor system performance and/or design, in near- and far-term applications.

Combustion stability continues to be a problem for the near future which engine manufacturers need to address. As we begin to define the contributors to combustion instability, corrective actions to minimize this problem area may become more obvious. At this time, improved fuel/air management is under examination as a possible solution to rumble. In the future, continued use of high bypass fans as well as variable stream engines will change the nature of combustion stability problems from previous experiences to new, more complex difficulties.

In the past, model and rig tests have supported most of the augmentor research. An advanced augmentor full-scale research and development effort to study alternate design concepts is an upcoming future need. Innovative design concepts are necessary

to meet current and future performance demands required of afterburning systems. A variable stream or variable-geometry augmentor is a possibility, as is the development of the swirl design concept.

As the temperature rise in main combustors continues to increase and the turbine continues to accept higher temperatures in fewer stages, augmentors will also be required to sustain higher temperatures. Flameholders will require new material for improved durability, or perhaps different flameholding concepts will need to be examined. Higher temperatures in the augmentor will also affect the cooling concepts used today, requiring the investigation of new liner materials and advanced cooling techniques.

An area of interest to augmentor designers, identified as a technology need in the past, is presently in its final stages of refinement. That need was for an afterburner modeling program to study the rumble phenomenon and to define a predictive technique which will identify the onset of a rumble condition based on the design and operating characteristics of the afterburner. Upon completion of this modeling concept, augmentor designers will have available a new analytical tool for future augmentor design and development.

It is apparent from this technology assessment of the afterburning system that the most significant payoffs for implementing advanced technology will be in the areas of increased performance, stability and operating conditions. Specifically, many of the future augmentor needs for USAF aircraft will be directly addressed during the conduct of the following research and development activities: 1) increasing stability in the upper left corner of the operating envelope, 2) reducing dry pressure loss and pressure spikes (which can contribute to stagnation stalls), and 3) designing shorter augmentation systems. The needs, cited by this assessment, are not intended to be categorized as an all-inclusive group of deficiencies which require advanced technology for improvements. Originality in augmentor design will always be welcome.

3. COMBUSTION MODELING

The technology needs identified by the engine companies fall into technology base and theoretical model advancement categories. Both needs are very similar to the point that careful design of research programs could provide the information needed in both categories. The most surprising need found in the survey responses was an almost universal need to replace and improve the fundamental aerodynamic design information which has been in use since the 1950's. Hole discharge coefficients, jet penetration/mixing data, diffuser performance parameters, cooling effectivenesses and hole-shape influences are some of the areas where new/improved design information is needed. Similarly, fundamental aerodynamic data are needed to validate and extend the multi-dimensional models being developed. More difficult to obtain are high temperature material properties for plastic stress theory development, radiation heat transfer data for hot gases and improved hydrocarbon system reaction rates. The greater the involvement of the company with advanced theoretical models the more concern that was expressed for the advancement of sophisticated theories, such as turbulence models or plastic stress theory.

A very important, but unexpected need, is not technology but more accurate and complete reporting. Most publicly available reports are incomplete to the point that the data cannot be utilized to validate models. It is recognized that greater detail is difficult to include, especially in society published papers. However, significantly more complete reporting needs to [illegible] established. Reports covering Government-sponsored research [illegible] open to immediate improvement. One possible aid to improved [illegible]rnment reporting is to establish informal peer group reviews [illegible]rt drafts. Reporting which allows duplication of the [illegible] data would greatly accelerate the validation and development [illegible]ed models.

[illegible]acement and improvement of the fundamental aero-[illegible] data is the single most universal and important [illegible]. Laser instrumentation is viewed as having the

capability to provide high resolution, high accuracy data without itself perturbing the flowfield. Many of the flowfields in today's complex combustors cannot practically or reliably be investigated by any other methods to date. Conditions such as those found between two dome swirl cups are radically changed by the physical presence of any instrumentation.

To be able to extend today's design capability, a great deal more must be known about the parameters which influence given flowfields. Classical jet penetration data correlate the effects of relatively few influencing parameters such as depth of penetration, penetration angle and mean centerline as a function of jet-to-crossflow momentum ratios. A great deal of additional information needs to be known regarding the influence of jet-to-crossflow temperature ratios and turbulence levels. Supply plenum or shroud velocity, angle and turbulence effects can influence the jet's character. Swirling flowfields from concentric swirl cups have not been parametrically investigated or characterized in detail. The effects of swirl between swirl cups in annular combustors are the major influence in the hot streak problems experienced by many of today's combustion systems.

The fundamental data that need to be obtained are very appropriate for collection by universities. However, work in this area by universities must be closely coordinated with the engine companies. The great amount of information that must be obtained should be as close as practical to conditions typical of aircraft gas turbine engines. The experimental setup and flow conditions must be general enough to make the data universally applicable.

The collection of fundamental design data by nonintrusive instruments offers a second extremely valuable opportunity to provide data for aerodynamic, combustion and kinetic models comparison. Very simple geometries and flow conditions can be accurately defined to establish model accuracy under the most fundamental conditions. A series of experiments to study the effects of geometric changes and flowfield conditions on a step-by-step basis can then be used to evaluate where a model loses

its quantitative and qualitative prediction capabilities. Ideally, a complete series of tests could be formulated which would embody all of the fundamental types of flow conditions found in an annular gas turbine combustor for both cold and burning conditions.

Heat transfer is the most difficult area in which advancements are needed. Before convection modeling in gas turbine combustors can be improved, our capability to model the interior flowfield and heat release must be greatly improved. Radiation in gas turbine combustors is a very significant portion of the total heat transfer load. A great deal more information about the local emissivity and absorptivity of the flame must be known before radiation models can be realistically useful. Many additional factors, such as view factors, pressure effects and temperature field, are needed before realistic radiation calculations can be made. In factors such as the temperature field of a combustor, the accuracy with which the aerodynamics, mixing and chemistry can be predicted play a major role in the accuracy to which radiation can be modeled. Improvements in gas turbine radiation modeling are seen as requiring long-term efforts.

Advancements needed in structural stress modeling are primarily dependent upon the development of plastic stress theory. Since structural needs are discussed elsewhere, no additional comments will be made here.

Fuel spray modeling is very important to practical combustor modeling. Fuel spray modeling involves several different processes. Fuel filming, film breakup due to air disturbances, droplet size determination, droplet/air interaction, vaporization, droplet versus cloud burning and pressure effects upon atomization are predominately empirically modeled phenomena due to the very complex fluid/air dynamics involved. The ability to predict the atomization characteristics of a nozzle for a particular fuel, the spray patterns produced and the fuel/air interaction determine our capability to predict fuel placement and the chemical flowfield that results.

Chemical kinetics is also a very important area to combustion modeling. The technological needs in this area are being addressed

on three main fronts: 1) global reaction models which yield heat release and species concentrations of the major products/pollutants, 2) improved reaction rate determinations, and 3) improved stirred reactor matrix models. The improvement of individual reaction rates has been left to the theoretical chemistry field. More basic reaction rate investigation is needed to support improved combustion modeling.

The most important technology need for aerodynamic models is an improved datum base. As discussed above, detailed descriptions of flowfields ranging from the most basic geometry and flow conditions to near practical systems are needed. Turbulence is the key weak link in the cold flow aerodynamic modeling process. A major part of the detailed experimental investigations should be full descriptions of the field's turbulence structure. Experiments which proceed from laminar to high turbulence levels are needed to provide the datum base necessary to develop a universal turbulence model. The experimental data must cover many basic flowfields such as boundary layers, recirculation zones and shear jets. Turbulence must be well-defined before its theories can be extended to reacting flows. The influence of combustion on turbulence may then be studied by duplicating the aerodynamic experiments with a reacting flowfield. The development of an accurate turbulence model will have a major impact on our ability to quantitatively predict reacting combustor flowfields. Advancements in our modeling capability will directly translate to improvements in our ability to design practical combustion systems for gas turbine engines.

The availability of detailed aerodynamic data will provide more rapid development of advanced turbulence models such as the Reynolds stress model. The advanced turbulence models require multi-axis data offered by laser instrumentation to validate and support their development.

New aerodynamic and chemistry models intensify numerical errors. Two important problems are artificial viscosity and "stiff" equation solutions. The complex flowfields in multi-dimensions being computed today are significantly affected by

artificial viscosity. A major source of large artificial viscosity errors is the computation of high gradients in regions of low grid density. Practical computer limitations dictate low grid densities when attempts are made to calculate large, complex, reacting or three-dimensional flowfields. High values of artificial viscosity act to "smooth out" the computed flowfield. New differencing, linearization and other numerical techniques are needed to prevent cumulative errors, such as artificial viscosity, from overwhelming the solution. In addition, "stiff" equation systems result in prohibitive computer time costs to obtain a solution. New techniques are needed to accelerate the convergence rate of stiff partial differential equations. Without improvements in numerical errors, accurate assessments cannot be made of the errors in physical models.

4. STRUCTURAL AND MECHANICAL DESIGN

The combustor mechanical/structural/life technology needs can be divided into areas of analysis (heat transfer, stress/strain, life prediction), testing (bench, rig and engine), materials/coatings and fabrication. The primary requirements in analysis are the development and verification of programs in the areas of plasticity, creep, 3-D finite element stress/strain prediction, failure mode life predictions (LCF, creep/stress rupture, erosion/corrosion/oxidation...), and heat transfer with thermal temperature distributions caused by cooling effects. Bench, rig and engine tests are essential in order to collect the data needed to verify the analytical predictions and to demonstrate combustor durability in a realistic environment. It is essential that the testing and analytical prediction model development go hand-in-hand, and that one builds upon the other. Extensive test instrumentation and utilization of past failure experience will be required in order to verify heat transfer coefficients, temperature distributions, stress/strain distributions and life capability. In addition, more emphasis is required in the development of material capabilities and material strength characterization (testing) for the high temperature combustor environment. Improvement of fabrication processes is required to produce the high temperature materials in complex combustor shapes at reasonable cost.

The generation of analytical prediction, testing, materials and fabrication procedures represents a challenge which cannot be avoided if combustors are to keep pace with other turbine engine components. This area has been neglected too long, and to avoid combustor mechanical/structural/life technology from limiting 1990 turbine engine development, these efforts should be initiated in the early 1980's.

5. ALTERNATIVE FUELS AND EXHAUST EMISSIONS

a. Alternative Fuels

In preparing for utilization of alternative fuels, it is recommended that programs be continued to determine the relationships between fuel property variations and combustor performance/durability. Investigations should include numerous current systems. Rig testing of components as well as full-engine tests are advocated.

Concurrent with the above effort, fuel/combustor effects information should be utilized to establish the importance of fundamental fuel properties in influencing the life and performance of system hardware. The ultimate goal is to reduce the specification of aviation turbine fuel to limitations on certain fundamental fuel properties. In addition to achieving greater simplicity, the specification would become more universal in that it would be independent of the source of hydrocarbons from which the fuel is derived.

In this progression, the final step is to utilize the information generated on fuel property/combustion effects relationships to influence the design of new combustion systems. Fuel flexibility should be made a part of the design criteria and the system's insensitivity to fuel property variations should be demonstrated.

A specific problem area has also been identified as requiring special attention. Fuel thermal stability is tractable with our current level of understanding. Designers are careful not to allow fuel temperatures to exceed a certain value (typically 300°F) prior to injection into the combustor. This approach has

been reasonably acceptable for petroleum-based fuels. However, since the fundamental process of thermal degradation of a fuel is not understood, the characteristics of this problem in a non-petroleum fuel may prove detrimental to current systems. Hence, continued work in the area of characterization of the thermal stability phenomenon is required.

In general, to prepare for utilizing alternative fuels in aircraft gas turbine engines, a more fundamental understanding of the fuel and its effect on performance and durability is required. This understanding is not only useful in assisting designers in planning a fuel flexible system, but also in defining a fuel specification that can be universally applied to fuel from any hydrocarbon source.

b. Exhaust Emissions

Having recognized the limitations of fixed geometry in satisfying all the emissions goals, the primary recommendation for continued work is in improving and developing the techniques of fuel-staging and variable-geometry. Supplemental to these efforts, continued work in improving fuel atomization is suggested. In the near-term, it is expected that fuel will continue to be injected as a liquid. Quick vaporization of the fuel and suitable dispersion of the fuel in the primary zone is critical to maintain combustors of reasonable size and to take full advantage of fuel staging and variable-geometry developments.

One final recommendation concerns the need to develop improved cooling techniques or higher temperature materials for reducing coolant airflows in the dome and forward liner. In that a significant contribution to low power emissions is the quenching of reactions that occur near the walls of the dome and liner, it is desirable to reduce or eliminate the cooling air required by hardware surrounding the primary flame zone.

SECTION V
FIVE-YEAR TECHNOLOGY PLAN

As a result of this technology assessment, a long-range research and development plan has been formulated. It is based on a combination of on-going/near-term requirements and a prioritized list of technical needs. Each technology need represents an area of research recommended by one or more of the participating engine companies. A total of twenty-seven individual programs are identified, fifteen of which have become part of the FY80-85 Combustion Technology Long-Range Plan. Table 1 is the prioritized listing of all programs identified from the Technology Assessment. Table 2 represents the Long-Range Plan developed from this Technology Assessment. This plan draws from the Technology Needs list only those top priority programs which can be effectively integrated into the overall Turbopropulsion Technology Plan consistent with projected long-range mission/system requirements for the Air Force. It should be noted, however, that this long-range plan is only accurate to approximately FY82; beyond a two-year projection many changes can always occur. Each year all programs are reconsidered relative to projected needs, emphasis, priority and importance to the Air Force. Consequently, a number of the "out-year" programs could shift in schedule or be replaced by new programs considered to be of greater importance at that time.

The remainder of this section contains individual program descriptions of each Technology Need. One will note that no programs dealing specifically with alternative fuels and/or exhaust chemical emissions research are included in the Technology Needs list. All alternative fuels programs are still in a preliminary development state. Consequently, no dedicated combustor hardware development efforts emphasizing use of broad-specification fuels are anticipated during the next five years. A number of programs emphasizing fuels effects, however, will be conducted to establish the impact of selected alternative fuels on current combustion system hardware and performance. With

regard to exhaust emissions research, little or no activity is planned over the next five years. Emissions characterization work will continue to be a part of all combustor development programs; however, no dedicated research is planned.

TABLE 1

TECHNOLOGY NEEDS -- PRIORITIZED LIST

1. AUGMENTOR STABILITY MANAGEMENT PROGRAM
2. COMBUSTION MODEL VALIDATION AND DIAGNOSTIC SUPPORT
3. ADVANCED COMBUSTOR LINER STRUCTURAL ENHANCEMENT
4. LIGHTWEIGHT, LOW COST SHINGLE COMBUSTOR
5. COMBUSTOR INLET DIFFUSER PERFORMANCE
6. COMBUSTOR/DIFFUSER INTERACTION EFFECTS
7. JET FLOW AERODYNAMICS INVESTIGATION
8. COMBUSTOR DOME DEVELOPMENT PROGRAM
9. INTERACTIVE GRAPHICS FOR ANALYSIS OF ADVANCED COMBUSTOR DESIGN
10. ADVANCED AUGMENTOR DESIGN
11. ADVANCED COMPACT COMBUSTOR
12. DEFINITION AND VERIFICATION OF COMBUSTOR ACCELERATED LIFE TEST
13. COMBUSTOR DOME FLOWFIELD INVESTIGATION
14. FUEL DISTRIBUTION/HEAT TRANSFER INTERACTION STUDY
15. FRONT-END DESIGN EFFECTS ON LEAN BLOW-OUT AND IGNITION LIMITS
16. LIGHTWEIGHT, LOW COST SHINGLE COMBUSTOR CYCLIC DURABILITY DEMONSTRATION
17. HIGH TEMPERATURE AUGMENTOR
18. SWIRL DISTORTION INFLUENCES ON THE DIFFUSER
19. ANALYTICAL MODELING OF COMBUSTOR/DOME AERODYNAMICS
20. ADVANCED LINER AND COATINGS FOR HIGH ΔT COMBUSTORS
21. LIFE PREDICTION ANALYSIS AND MODEL VALIDATION
22. PHOTOCHEMICAL/LASER-ASSISTED COMBUSTION
23. COLD START IGNITION/ALTITUDE RELIGHT CHARACTERIZATION OF LOW VOLATILITY FUELS
24. ADVANCED AUGMENTOR LINER COOLING
25. DOME/INJECTOR EFFECTS ON OFF-DESIGN PERFORMANCE
26. MAIN COMBUSTOR RESONANCE
27. DEVELOPMENT OF A PLASTICITY ANALYSIS FOR COMBUSTOR SYSTEM APPLICATION

1. AUGMENTOR STABILITY MANAGEMENT PROGRAM

OBJECTIVE: To develop a fuel management/distribution computer model and integrate into an improved version of the existing "rumble" stability computer program developed under the Lo-Frequency Augmentor Instability Investigation (USAF Contract F33615-76-C-2024).[4]

APPROACH: (1) A two-phase fuel flow distribution model of the augmentor fuel system will be developed accounting for both transient and steady state operating conditions.
(2) The existing "rumble" stability computer code will be extended to eliminate code limitations and improve numerical efficiency.
(3) A new contractor-furnished augmentor fuel distribution system will be evaluated under the USAF/NASA FSER program, the results of which will be compared to model predictions.

PAYOFF: Refined rumble model will provide a useful engineering design/support tool for future augmentor systems development to assure high performance rumble-free operation about the flight envelope.

2. COMBUSTION MODEL VALIDATION AND DIAGNOSTIC SUPPORT

OBJECTIVE: To extend existing 2-D axisymmetric and 3-D reacting flow combustor models incorporating the latest refinements in chemical kinetics, turbulence, heat transfer and numerical procedures.

APPROACH: Existing analytical combustor models will be upgraded and an experimental diagnostics support program will be conducted to define the reacting flow characteristics of the combustion processes. The AFAPL combustion tunnel will be used during the experimental program, the test results of which will be applied to the analytical model.

PAYOFF: This work will support the continuing development of analytical design tools for turbine engine combustors, thus, reducing hardware design and development time.

3. ADVANCED COMBUSTOR LINER STRUCTURAL ENHANCEMENT

OBJECTIVE: To develop the required analysis tools and experimental datum base in order to improve combustion hardware structural durability while providing an accurate means for predicting/projecting combustion system life.

APPROACH: This program will be conducted in basically three (3) phases:
(1) Phase I will establish the state-of-the-art for combustor structural stress/strain analyses, heat transfer and life prediction. Existing turbine analysis procedures will be applied where appropriate.
(2) Phase II will define an in-depth datum base of required temperature, stress, strain and heat transfer information consistent with the experimental support needs of the analytical tools identified from Phase I.
(3) Phase III will be a model validation effort drawing upon the experimental data of Phase II. Basic model shortcomings and limitations will be identified for further computer code development and refinement.

PAYOFF: Will provide the first step in defining essential structural analysis and life prediction design tools for combustor application.

4. LIGHTWEIGHT, LOW COST SHINGLE COMBUSTOR

OBJECTIVE: To design, fabricate and test a shingle combustor using lightweight materials and advanced thermal barrier coatings. Final configuration is to provide a weight and cost savings of 25-40 percent over current shingle combustor designs.

APPROACH: (1) The strength, temperature, oxidation resistance and chemical interaction properties of candidate shingle materials and advanced thermal barrier coatings will be evaluated for potential application to the shingle combustor design.
(2) A full-annular combustor will be fabricated and rig tested at both steady state and transient conditions consistent with both contemporary and ATEGG combustion system requirements.
(3) Using an available F101 or F101X engine, the new shingle combustor will undergo a full SL engine evaluation at both steady state and transient conditions.

PAYOFF: Reduction in cost and weight of the shingle combustor will permit more rapid technology transfer of this advanced design to conventional engine systems. The projected high durability and long life characteristics of the shingle design offer substantial improvements in engine hot part life cycle cost.

5. COMBUSTOR INLET DIFFUSER PERFORMANCE

OBJECTIVE: To study the causes of aerodynamic losses in the combustor diffuser flowfield. To identify those loss mechanisms of consequence and determine the loss tolerance of a range of diffuser designs to those loss mechanisms, i.e., the straight dump versus the vortex-controlled design.

APPROACH: Conduct a detailed experimental investigation of the diffuser flowfield of interest using noninterference flowfield mapping techniques. Develop an aerodynamic flowfield prediction model of the diffusion process using the experimental data for model validation.

PAYOFF: An accurate design and performance prediction capability will aid the designer in minimizing inlet diffuser losses thus improving cycle performance relative to thrust and SFC.

6. COMBUSTOR/DIFFUSER INTERACTION EFFECTS

OBJECTIVE: To examine the performance/aerodynamic influences and loss mechanisms that are controlled by the size, shape and axial/radial location of the combustor relative to the inlet diffuser.

APPROACH: Perform a detailed experimental investigation of diffuser flowfields in combination with an in-depth parametric study of the isolated influences of different combustor sizes, shapes and locations. Develop a supporting aerodynamic flow model to describe the observed diffuser/combustor interactions.

PAYOFF: This research will provide a better understanding of the interaction effects of the combustor on the diffuser which should lead to optimized interface design procedures for reduced flowfield losses.

7. JET FLOW AERODYNAMICS INVESTIGATON

OBJECTIVE: To extend and/or update the available information and knowledge on jet discharge coefficients, jet penetration and jet mixing characteristics as a function of influencing flow conditions.

APPROACH: Those flowfield conditions which influence jet discharge coefficients, penetration and mixing will be experimentally investigated. A variety of hole sizes and shapes will be examined consistent with what one might design into a combustor liner. In parallel to the experimental work will be the development and/or extension of an appropriate jet flow model describing the flowfield aerodynamics in and around a typical combustion, dilution or cooling jet.

PAYOFF: Better understanding of jet flow mixing and penetration characteristics will provide the designer improved insight into hot streak formation, control and suppression. This, in turn, leads to improved hot section durability and life.

8. COMBUSTOR DOME DEVELOPMENT PROGRAM

OBJECTIVE: To investigate the nature of combustor hot streak formation resulting from flowfield regions of high fuel concentration contributing to high pattern factor and downstream hot-section distress. (This is a joint program with the Navy (NAPC) for which the Navy is the contracting agency.)

APPROACH: A multi-phase program will be conducted to improve the primary zone of the GE ATEGG combustion system. Flowfield aerodynamics, fuel/air mixing and distribution and geometry effects will be examined both analytically and experimentally. Variable-geometry features for primary zone airflow distribution control will be investigated. The results will be incorporated into the combustor design of an advanced development gas generator.

PAYOFF: Improved dome designs leading to suppression or control of hot streaks will extend hot-section life, reduce the time for pattern factor development and improve exit temperature gas path uniformity into the turbine.

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9. INTERACTIVE GRAPHICS FOR ANALYSIS OF ADVANCED COMBUSTOR DESIGN

OBJECTIVE: To provide fully interactive graphic Cathode Ray Tube (CRT) technology for analysis of operational aspects of turbine engine combustors. To provide the capability to analyze airflow characteristics of combustion systems.

APPROACH: Conversion of current combustor computer programs with the inclusion of new combustor technology to an interactive CRT system. This will be an in-house program drawing upon the interactive graphics capability developed for the turbine design system.

PAYOFF: This CRT package will provide the design engineer quick information on the effect of various changes made to combustor geometries and operating conditions. The program will provide more detailed information on the operational characteristics of current combustion systems.

10. ADVANCED AUGMENTOR DESIGN

OBJECTIVE: To define and develop advanced component design technology for a new wide modulation augmentor system for mixed-flow turbopropulsion augmentor application. New, radically different design techniques will be considered, i.e., swirl and variable-geometry augmentors.

APPROACH: Analytical and preliminary experimental investigations will be conducted to establish basic concept design capabilities/limitations. Improved ignition, fuel injection, flame stabilization, liner cooling, pressure loss and wide fuel/air modulation will be emphasized throughout this program.

PAYOFF: A radically new augmentor design for advanced turbofan systems will permit performance improvements in both pressure loss and combustion efficiency, 50% reduction in dry pressure loss and increases in combustion efficiency to 95% or greater.

11. ADVANCED COMPACT COMBUSTOR

OBJECTIVE: To design, fabricate, develop and test an advanced compact combustion system for tactical propulsion system application. Design goals will include demonstrated operation to near stoichiometric fuel/air ratios but with wide turndown and inlet Mach number capability.

APPROACH: A compact, short-length combustion system will be developed. Advanced fuel injection and programmed fuel distribution will play a key role in this program to assure wide temperature modulation capability. Variable-geometry will be considered to optimize air distribution and combustion efficiency at all power settings. Both transient and steady state performance will be examined.

PAYOFF: This program will establish virtual design limits in combustion system size providing the necessary technology for a compact, high performance propulsion system for advanced fighter application.

12. DEFINITION AND VERIFICATION OF COMBUSTOR ACCELERATED LIFE TEST

OBJECTIVE: To establish the pertinent data/information needed to develop and validate an accelerated life test procedure in order to define combustor life and structural reliability characteristics.

APPROACH: This program will consist of three phases:
(1) Past engine field and ground cyclic test experiences will be reviewed relative to combustor durability and life. Analytical correlations using field data will be developed for initial life prediction.
(2) A specialized test procedure defining a representative test cycle to verify combustor life capabilities will be developed. This will include the definition of a mix of appropriate tests, i.e., steady state, cyclic, sea level, altitude and rig and engine.
(3) A validation of the accelerated life test defined during Phase III will be conducted using either rig or engine or both.

PAYOFF: A representative accelerated life test for the turbine engine combustor will be defined allowing early combustor durability and life prediction.

13. COMBUSTOR DOME FLOWFIELD INVESTIGATION

OBJECTIVE: To provide an experimental datum base on combustor flow patterns in the region upstream of the combustor dilution plane. To characterize the swirler and primary jet flow interactions and to examine fuel injection momentum exchange effects on primary zone flow.

APPROACH: Pressure profiles and LDV mappings of combustor dome flow velocity patterns will be obtained from a variety of conventional geometry combustor dome configurations. Swirl strength, primary jet strength and recirculation zone size and shape will be determined. Fuel injection effects on primary zone aerodynamics will be studied to include both gaseous and liquid injection under cold flow conditions.

PAYOFF: Data generated will provide valuable primary zone flowfield information for both 2-D and 3-D combustion models now under development. Program will also provide a quantitative understanding of the fuel injection/recirculation pattern interaction.

14. FUEL DISTRIBUTION/HEAT TRANSFER INTERACTION STUDY

OBJECTIVE: To assess effects of injector performance (spray uniformity and trajectory) and primary zone aerodynamics on combustor wall heat transfer. To improve understanding of the coupling between these phenomena relative to wall hot-spot location.

APPROACH: Using combustor simulations or segments of practical combustors, configurations which independently vary fuel spray placement and cooling/dilution schemes will be examined. Liner wall temperatures will be measured to determine both total and radiative heat transfer. Using an annular combustor, fuel injector placement and attendant fuel spray interactions will be characterized to determine wall heat transfer effects.

PAYOFF: Increased liner durability due to more even wall heating and reduced development time for new combustors due to wide applicability of the test results.

15. FRONT-END DESIGN EFFECTS ON LEAN BLOW-OUT AND IGNITION LIMITS

OBJECTIVE: To develop detailed test data on swirler/injector/primary hole design and interactions on both, lean blow-off and ignition limits. To assist in design of variable-geometry combustors with enhanced lean limits, ignitability and altitude relight.

APPROACH: Using combustor simulations or segments of practical combustor, a number of configurations will be tested to examine fuel spray placement, spark plug location, swirler configuration and cooling/dilution schemes to determine the lean blow-off and ignition limits. Laser velocimetry will be used to examine flow pattern detail for each configuration tested in order to establish these aerodynamic sensitivities which influence lean blow-off and ignition.

PAYOFF: Improved ignition, altitude relight and lean limit performance in fixed and variable gemoetry combustors. Reduced development time for new combustors due to wide applicability of the test results.

16. LIGHTWEIGHT, LOW COST SHINGLE COMBUSTOR CYCLIC DURABILITY DEMONSTRATION

OBJECTIVE: To evaluate the durability/life characteristics of the new shingle combustor developed under the previous concept development program. (Program No. 4)

APPROACH: A full annular cyclic durability test of the new lightweight shingle combustor will be conducted. The demonstration test will simulate full cyclic engine operation including simultaneous variation in pressure, temperature air flow and fuel flow. A fighter mission cycle will be the test cycle. (This is a follow-on to the previous concept development program and will utilize the General Electric LCF combustor test rig.)

PAYOFF: Successful completion of this program will accelerate the technology transition process of the shingle liner design to near-term propulsion system application.

17. HIGH TEMPERATURE AUGMENTOR

OBJECTIVE: To develop the necessary design technology for a high temperature turbojet augmentor capable of providing a wide range of thrust modulation consistent with the thrust/flight Mach number demands of a variable-geometry, variable-cycle turbojet engine.

APPROACH: A full size turbojet augmentor will be designed, fabricated, developed and tested under this program. Variable-geometry flameholding devices will be examined for low loss nonaugmented operation. Inlet temperatures ranging from 1200°F to 2200°F will be considered to cover the modulation range of the augmentor as a function of core cycle temperature.

PAYOFF: This high temperature augmentor will add additional thrust flexibility to a high performance, high temperature rise turbojet engine where weight and cost incentives for a high Mach aircraft make the augmented turbojet an attractive cycle.

18. SWIRL DISTORTION INFLUENCES ON THE DIFFUSER

OBJECTIVE: To gain a better understanding of the effects of swirl on the performance of annular diffusion systems and to quantify performance losses due to swirl.

APPROACH: The effects of compressor discharge swirl on the performance of an annular diffuser will be experimentally examined using a cold flow test rig. The effects of inlet swirl on diffuser wall boundary layers, the presence of struts and boundary layer bleeds will be investigated. A range of representative swirl angles will be studied and the performance impact relative to diffuser pressure loss, pressure recovery and aerodynamic stability as a function of both swirl angle and flowfield Mach number will be determined. In addition, a swirling flowfield diffusion model will be developed which can analytically describe the diffusion characteristics of a swirling flowfield in a combustor diffuser.

PAYOFF: This program will provide a better understanding of the influences and loss generating mechanisms caused by swirl on diffuser performance.

19. ANALYTICAL MODELING OF COMBUSTOR/DOME AERODYNAMICS

OBJECTIVE: To validate elliptic, three-dimensional, turbulent, nonreacting flow codes, both one and two phase, for practical combustor designs, by comparison with the experimental data obtained from the Combustor/Dome Flowfield Investigation.

APPROACH: Using inlet and boundary conditions determined in the experimental program and an appropriate flow code, compare the flowfield calculated to just upstream of the dilution holes or primary zone model exhaust with the experimental results (velocities, three-dimensional mean and fluctuating, wall pressure profiles). The complexity of the model should be increased as follows: (1) no injection, air flow; (2) gas injection, airflow; (3) liquid injection, airflow (include only interphase momentum transfer).

PAYOFF: Increased confidence in the ability of cold flow codes to predict flows in practical geometries. More rapid utilization of such codes in the combustor design process.

20. ADVANCED LINER AND COATINGS FOR HIGH ΔT COMBUSTORS

OBJECTIVE: To apply recently developed materials and coatings to the combustor liner in order to improve the erosion properties, the LCF capability and the maximum useful temperature of the combustor liner. Also included in this program will be the improvement of cooling technology for the reduction of cooling requirements.

APPROACH: This program will consist of three (3) phases:
(1) Phase I will study several selected materials and coatings to determine which material/coating system will provide the maximum payoff for a given combustor liner application. Included in this phase will be specimen testing evaluating each material and coating.
(2) Phase II will be a design effort. This phase will include both conceptual and detailed design analysis. Upgrading of current cooling technology will be the major area of emphasis along with applying the new material and coating technology.
(3) Phase III will fabricate and test the new liner design. The combustor test will be heavily instrumented to evaluate actual results versus those predicted in the design phase.

PAYOFF: This program will provide an initial step toward making better usage of new materials being developed for improved combustor life and performance.

21. LIFE PREDICTION ANALYSIS AND MODEL VALIDATION

OBJECTIVE: To develop a correlation between gas turbine engine usage and actual component life accounting for those sensitivity factors having a significant effect on combustor durability.

APPROACH: This will be a three phase program:
(1) Define performance, stability and life trade-offs for one or more military engine combustion systems. Usage data from a well-defined commercial engine family will be used as a reference baseline.
(2) Correlate usage data with regard to the military engine combustor life factors, including design and actual engine thrust loading requirements as a function of combustion life. In addition, thermal load sensitivities to specific design conditions such as starting, low Mach number, high altitude flight operation, pressure drop, restarting and combustor pattern factors will be investigated.
(3) The results of Phases I and II will be incorporated into the development of a combustor design methodology program for calculating combustor life for a representative usage environment.

PAYOFF: This program will provide a coherent approach to combustor design resulting in improved durability and life prediction.

22. PHOTOCHEMICAL/LASER-ASSISTED COMBUSTION

OBJECTIVE: To study the means by which light sources might be used to initiate, stabilize and accelerate combustion processes. Possible applications include main burner ignition and stabilition, afterburner ignition and flameholding, and ramjet combustion efficiency improvement.

APPROACH: A three phase approach will be taken: (1) quantitatively establish and verify enhancement effects under conditions of interest, (2) study known problem areas for application (i.e., boundary layer penetration), (3) conceptualize application.

PAYOFF: This new concept has potentially high payoff in improving performance and ignition limits of turbine engine main burners, afterburners and ramjet combustors.

23. COLD START IGNITION/ALTITUDE RELIGHT CHARACTERIZATION OF LOW VOLATILITY FUELS

OBJECTIVE: To improve starting and altitude relight capability of high density and/or high flash point fuels for cruise missile and aircraft engines.

APPROACH: Using information developed under the Front-End Design Effects program, investigate optimal fuel injector/primary zone aerodynamics configuration for low volatility fuels. In rig tests, vary type and location of igniter, as well as fuel volatility. Simulate cold soak as experienced by the cruise missile and windmilling conditions in the aircraft.

PAYOFF: Improved ignition and altitude relight in airbreathing engines operating on low volatility fuels.

24. ADVANCED AUGMENTOR LINER COOLING

OBJECTIVE: To develop an advanced, high temperature cooling concept for augmentor liner application drawing upon available superalloy materials, thermal barrier coatings, etc.

APPROACH: The design, fabrication and test of an advanced augmentor liner cooling scheme will be conducted. Utilization of existing high temperature alloy materials and thermal barrier coatings will be considered. A structural, stress and life prediction analysis will be conducted on the final design. Liner cooling conditions consistent with both a turbofan and a turbojet augmentor will be examined. Testing will be constrained to subscale sector hardware only.

PAYOFF: Improved augmentor liner cooling will increase liner life, reduce cooling air requirements and improve overall augmentor combustion performance.

25. DOME/INJECTOR EFFECTS ON OFF-DESIGN PERFORMANCE

OBJECTIVE: To assess effects of injector performance (spray uniformity and placement) and primary zone aerodynamics on combustor part-power efficiency.

APPROACH: In simulations of combustors or segments of practical combustors, a number of configurations will be rig tested which vary independently fuel spray trajectory and cooling/dilution schemes. Part power combustion efficiency will be determined. Reaction quench regions will be characterized. In annular configurations, injector-to-injector interaction will be characterized as well.

PAYOFF: Increased off-design combustion efficiency due to improved design techniques will enhance part power performance.

26. MAIN COMBUSTOR RESONANCE

OBJECTIVE: To investigate both analytically and experimentally the stability characteristics of high performance main combustors and establish the driving and damping mechanisms which contribute to the onset of an acoustic instability.

APPROACH: A multi-phase program will be conducted to examine combustion-driven resonance in the main combustor; an analytical model describing the stability characteristics will be developed; acoustic suppression techniques will be identified.

PAYOFF: Analytical design tools which evolve from this program will permit the development of high performance, high temperature rise combustors designed for resonance-free operation at all conditions.

27. DEVELOPMENT OF A PLASTICITY ANALYSIS FOR COMBUSTOR SYSTEM APPLICATION

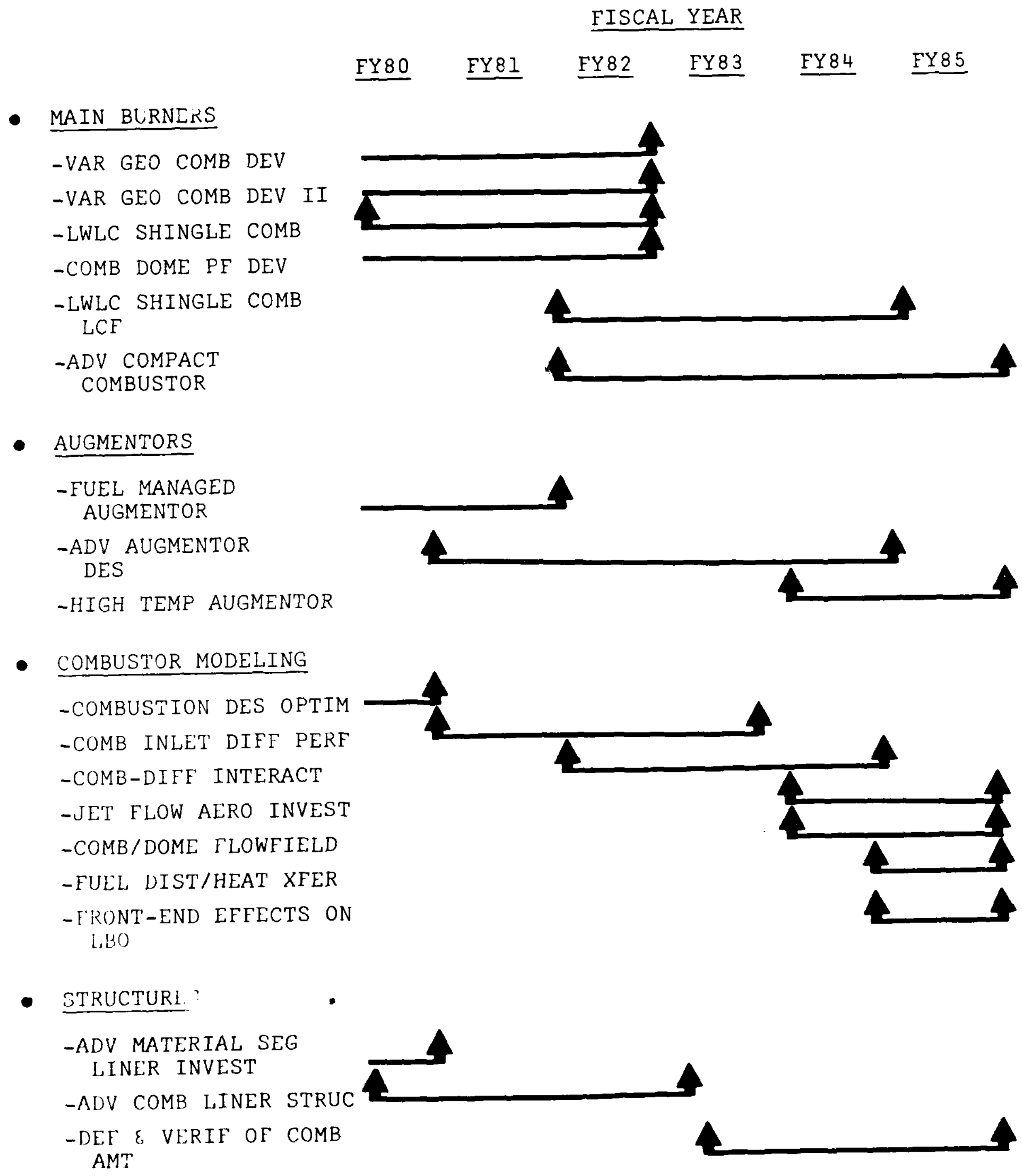
OBJECTIVE: To develop a detailed high temperature plasticity analysis in order to more accurately define combustor stress/strain levels resulting from applied aero-thermal loads.

APPROACH: A program review of available plasticity analytical procedures which can handle the combustor high temperature environment and geometric constraints will be conducted. The most representative model will be selected on the basis of stress level calculation accuracy, ease of modeling and computational time. This procedure will then be programmed and validated using a test case with experimental data as verification.

PAYOFF: Improved analytical procedure for predicting combustor stress/strain at high temperatures.

TABLE 2

COMBUSTION TECHNOLOGY LONG-RANGE PLAN



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APPENDIX

TURBOPROPULSION COMBUSTION TECHNOLOGY ASSESSMENT

COMBUSTION TECHNOLOGY GROUP
AIR FORCE
AERO PROPULSION LABORATORY
WRIGHT-PATTERSON AFB OHIO

TECHNOLOGY ASSESSMENT

Table of Contents

I. Design Methodology

The Government's physical separation from the practical details involved in combustion system design diminishes its understanding of industry's procedures and practices. The purpose of this section of the Combustion Technology Assessment is to reduce this gap of understanding. The questions raised in this section are intended to establish techniques used, their level of technology and the accuracy and adequacy of these techniques. The information provided in response to this section of the questionnaire will aid in the identification of those design technology areas which most need improvement.

Obviously, the responses to the questions of this section could be voluminous. Therefore, your responses should be limited to synopses of points of information which need to be transmitted. If graphs, charts or tables would be beneficial to the discussion, such additions are welcome. As an aid in responding to each question in this section, the following five topics should be addressed as appropriate:

- Practice - The current procedures used in designing or modifying a part of the combustion system.
- Goal - The configuration or performance objective to be achieved.
- Reasons - Why the goal configuration or performance is needed and the reasons behind the current practices.
- Problem Areas - What conflicting performance, configuration or manufacturing requirements cause difficulties in meeting design goals.

This format should be adjusted as necessary to insure adequate or eliminate unnecessary information.

A. Main Combustors

The design of a new combustion system begins with fundamental objectives for system performance. Restrictions are placed on the design by other components in the engine, yet new and higher performance goals are often established for the new system. In answering the following questions, please provide the general methods, techniques, and approaches utilized by your company in the design of the main combustor.

1. Discuss how design points are chosen for new combustion systems. In your discussion include interrelationships and tradeoffs made among performance parameters. Include items such as lean blowout/ignition, pressure drop, cooling, durability, temperature rise, turbine requirements (pattern factor, profile factor, cooling, etc.), idle operation, and aerodynamic loading.

2. Discuss your method of gross parameter definitions--in other words--choice of size and shape, length, dome height, injector type, etc. Discuss also your method of designing the detailed geometry of the combustor. How do

you incorporate considerations of air flow, heat transfer, analytical studies and experimentation?

3. Discuss how possible discrepancies in rig conditions versus engine conditions are considered in evaluating new combustor concepts.

4. After a combustor is designed and fabricated, unexpected performance variances frequently occur. Discuss your methods of problem identification and problem correction (e.g., pattern factor, hot streaks, cooling, etc.). Also discuss diagnostic techniques/methods which you employ during combustor development for problem definition/assessment.

5. Discuss "designing for production." Include in your discussion the importance of various considerations (e.g., sensitivity to tolerances, manufacturing techniques and feasibilities, etc.).

6. Discuss the correlation between primary zone equivalence ratio and final smoke emission.

7. Discuss the impact of designing for low smoke on altitude ignition.

8. Discuss differences you see in low power (idle) emissions between JP4 operation, JP5 operation, and other fuels tested.

9. Discuss rich primary zone combustion systems for NO_x reduction in light of the prospect of eventually using low hydrogen fuels. Discuss solutions to the smoke/flame radiation problems which might be encountered.

10. Discuss fuel thermal stability problems and the best approaches to handling the problems (design modification and/or strict fuel specification).

11. What combustor performance parameters have you seen to vary with different fuels (JP4, JP5, Diesel, etc.)?

12. Which trace metals and what quantity levels are detrimental to hot section parts? In what way are they a problem - corrosion/errosion/plating?

B. Augmentors

1. Discuss the process of selecting design goals, including tradeoffs between performance parameters (e.g., percent augmentation, pressure drop, altitude operation, etc.)

2. Discuss the mix of experiments and analysis (equations, correlations and tables) used in the design of an afterburner/duct burner system.

3. Discuss the interrelationships of flameholder geometry, fuel bars/rings, and mixers on efficient afterburning. The discussion should include effects of blockage and dimensional variations (i.e., radial, circumferential, spacing, angles, etc.) on fuel/air distribution and combustion stability.

4. Discuss how changes in upstream flow conditions affect augmentor

operation and how you avoid or minimize any of these adverse affects. Include in your discussion: 1) the effects of flight-induced flow distortion and; 2) the consequences of basic engine changes after the augmentor design is finalized.

5. Discuss your approach to avoiding or eliminating combustion instability in augmentor designs.

C. Mathematical Modeling

Increasing turbine engine hardware development costs and the complexity of advanced technology designs have increased the importance of modeling during the design process. The questions below are to provide us with the knowledge of the mathematical modeling that you employ. please provide short discussion answers for the questions in this section.

1. What is the relative importance to your design process and development process of theoretical models, empirical models and cut and test/"gut feeling?"

2. What are the advantages of each--the analytical and the empirical type models?

3. Do you rely mostly on hand calculated models or computer models?

4. How does this dependence vary with stages of development?

Mathematical models have rapidly grown more complex. Please discuss the following questions regarding the modeling techniques you use.

5. What type models are used in calculating design features (e.g., empirical, theoretical, 1-D, 2-D, etc.)?

- Aerodynamic Flow Distribution/ Performance
- Heat Transfer
- Structural
- Exhaust Composition
- Geometric
- Pattern Factor
- Ignition/relight/flame stabilization
- Efficiency
- Other

6. What are the supporting theories/empirical datum sources supporting the following general areas?

- Aerodynamics
- Chemistry
- Heat Transfer
- Structural Analysis
- Fuel Evaporation
- Sub-model coupling

7. What are the accuracy levels of the calculation procedures identified in Question 6?

8. What are their limitations (limits & causing factors) of applicability? (geometries, flow ranges)

9. What are the critical models/submodels that are used?

10. What are the accuracies and limitations of these models and submodels?

11. How do the combustion system physical constraints impact the models?

12. For what technology areas are multidimensional models considered important? Why?

13. What phenomena require multidimensional modeling for acceptable accuracy?

14. How do physical features impact the use of multidimensional models?

15. How great a role does "familiarity/hunches" play when using your theoretical models?

Memory size and run time are important considerations in how useful a computer model is. The goal of the following questions is to establish what are the practical, useful time, memory, and therefore cost limits. Variations of these limits for different technologies should also be discussed.

16. What is the relative importance between interactive and batch operation?

17. What size (core) is considered the practical limit?

18. What is the largest size that will be employed?

19. Do you have an average run cost goal? What is it?

20. What execution time is considered the practical limit?

21. What is the largest execution time that will be allowed?

D. Materials and Structures

Available materials, their cost, and requirements for structural integration of combustion system components into the engine system have traditionally constrained combustion system design. Please describe current practices, and current limitations (and known potential solutions) with respect to:

1. Materials selection philosophy used in combustion systems

- Composition and characteristics
- Materials properties - and relationship to needs
- Application limits
    - -- Standard
    - -- Maximum

- Safety factors and margins
- Non-metals versus super alloy materials

2. Material/Structural Analysis Methodologies

    - Types and complexity of analyses employed

        -- Empirical or Analytical
        -- Number of dimensions considered

    - Elastic and plastic stress considerations

        -- Static
        -- Dynamic

    - Vibratory stresses and fatigue
    - Thermal Analysis

        -- Structural influence
        -- Physical (dimensional) influence
        -- Heat transfer

II. Assessment of Technology Needs

Future technology will be guided by the results of current research efforts to meet the needs and desires of the combustion system designer. The object of this section is to determine which technologies are most needed or have the greatest promise of improving combustion system performance or design in order to develop a framework for the programming of technology development efforts.

Both near-term and long-term technologies are important in this assessment. Near-term efforts can usually be defined in terms of extending or improving current technology or practice by well-defined (scope, cost and manpower) efforts. Longer term efforts can generally be defined in terms of a desired capability for which there is little or no developed or postulated technology; consequently, the means of achieving their advantages are less well-defined.

Questions posed in this section are not all-inclusive. They represent Air Force/Government perceptions of current problem areas which areas which are provided as guides to industry to stimulate the definition of needs. Responses to this section will be used to establish priorities for future programs. Proposals for technology development are not, however, being sought. While costs, times, and risks may be considered, the information being sought should be a statement of the technology need which identifies the short-coming or deficiency being addressed. For each technology need identified, a relatively concise statement of objective, and projected payoff should be provided. A technical approach may be provided if one is identifiable.

A. Main Combustors

1. Discuss the weak points in main combustor design and development for each of the following areas. What could be changed or improved to produce better performance and/or a lower cost combustion system?

- Aerodynamics - diffuser, dome, combustor etc.
- Heat Transfer - combustor walls, fuel injectors and manifolds
- Structures
- Materials
- Chemistry - emissions, particle formation
- Geometry and sizing
- Design problem identification/correction
- Multifuel or alternative fuel consideration

2. Discuss possible way of overcoming or finding alternate means of achieving performance beyond current theoretical and physical limitations--such as altitude ceilings, extreme speeds (high and low), and fuel/air conditions.

3. Assess those technologies which will provide the greatest improvements in combustion systems design and performance: 1) in the near-term (next seven years); and 2) in the far-term (next fifteen years).

B. Augmentors

1. Discuss the known technology weakness/deficiencies relative to the design and development of augmentors.

2. Discuss the potential for improving the operational envelope of augmentors. Include in your discussion the areas of combustion stability and relight capability.

3. Assess those technologies which will provide the greatest improvements in augmentor system design and performance: 1) in the near-term (next seven years); and 2) in the far-term (next fifteen years).

4. Discuss any exotic new ideas for future augmentation systems or alternative means of thrust augmentation.

C. Mathematical Modeling

1. Which models are the most critical to your design system?

2. What techniques/new models are most needed to improve modeling accuracies and limitations? Quantify if possible.

3. What capability/information would most beneficially increase your use of models?

Appendix A. Historical Data

The objective of collecting historical data as part of this technology assessment is to provide a body of information which forms the perspective and baseline for the discussion corresponding to the previous sections of this questionnaire. Narrative responses are requested in the subsections dealing with combustors and augmentors. The third section requests a compilation of engine data in four tables. Many of these data may most easily be provided by component or layout drawings. It is requested that data be provided by engine model, with most recent models reported first. Since many of the ATEGG/advanced engine demonstrator data will be classified, appropriate protection requirements must be followed.

In addition to providing a baseline from which to evaluate this assessment of technology need, it is hoped that from the data provided in this section historical trends could be developed. These trends would then be assembled to provide a story of where gas turbine engines have been and where they can be expected to go in the future. If you have such information, charts and/or narrative currently available, its inclusion with data submitted for the histroical section would be greatly appreciated.

A. Main Combustors

Discuss how the combustion system geometry and operating parameters have changed and/or been improved through the years. Where possible, use graphical illustrations to show these changes, e.g., combustor temperature rise, cooling, and L/D as a function of time (years).

B. Augmentors

Discuss how geometry and operating conditions in afterburners have changed through the years. Include any differences that turbofan operation may present over turbojet afterburner operation. Where possible, include graphical illustrations to show performance improvements realized over the past several years, e.g. combustion efficiency and L/D as a function of time (years).

C. Engine Data

Please provide the data requested by the following four tables for each engine you have produced or are developing:

Table I: General Engine Information
Table II: Combustor and Augmentor Description
Table III: Main Combustor Performance
Table IV: Augmentor Performance

Component or layout drawings may be submitted if they most suitably provide the requested information. Narrative information may be submitted also to highlight development evolution or where appropriate to assist understanding of the data.

TABLE I

GENERAL ENGINE INFORMATION

ENGINE MODEL:

TYPE ENGINE[(1)]:

O'ALL DIAMETER, IN.:

O'ALL LENGTH, IN.:

DRY WEIGHT, Lb_m:

NO. OF SPOOLS:

RATED THRUST DRY, Lb_f (SLS):

RATED THRUST A/B, Lb_f (SLS):

MAX RATED AIRFLOW @ SLS, Lb_m/Sec:

BYPALL RATIO @ SLS:

ENGINE PRESSURE RATIO @ SLS:

MAX RATED BOT, [(2)] ^oR:

DESIGN SFC, Lb_m FUEL/HR/Lb_f:

MAX A/B - OVERALL SFC, Lb_m/HR/Lb_f:

(1) A/B-T/F: Afterburning Turbofan; A/B-T/J: Afterburning Turbojet; F: Fan; J: Jet; P: Prop; S: Shaft; LF: Lift Fan; ATEGG; JTDE

(2) Burner Outlet Temperature

TABLE II

COMBUSTOR AND AUGMENTOR DESCRIPTION

ENGINE MODEL:

MAIN COMBUSTOR, GENERAL

BURNER DESIGN LIFE HRS:

BURNER LIFE (FIELD-ESTIMATE), HRS:

CRITICAL LEAN BLOWOUT FUEL/AIR (STATE CONDITIONS):_______@_______

MIN IGNITION FUEL/AIR (SLS):

IGNITION ENVELOPE (GRAPHICAL ILLUSTRATION):

FUEL TYPE(S):__________,__________,__________

COMBUSTION SYSTEM LENGTH[(1)]:

COMBUSTOR LINER

TYPE COMBUSTOR:

NO. OF LINERS:

COOLING SCHEME:

SURFACE AREA, FT^2:

REFERENCE AREA, FT^2:

VOLUME, FT^3:

MATERIAL:

FABRICATION TYPE:

LENGTH, IN.:

PRIMARY/DILUTION HOLE TYPE[(2)]:

WEIGHT, Lb_m:

SUPPORT TECHNIQUE (FORWARD OR AFT):

(1) Compressor Discharge to Turbine Vane Inlet
(2) Plunged, flush, slot, etc.

TABLE II (continued)

DOME

DOME HEIGHT, IN.:

NO. OF SWIRLERS:

TYPE OF SWIRLERS:

COUNTER OR CO-ROTATING:

MATERIAL:

FUEL INJECTORS

TYPE FUEL DISTRIBUTION:

TYPE ATOMIZATION:

NO. OF INJECTORS:

IGNITION SYSTEM

TYPE IGNITION SYSTEM:

TYPE IGNITOR:

NO. OF IGNITORS:

EXCITER STORED ENERGY, JOULE:

DELIVERED SPARK ENERGY, JOULE:

SPARK RATE SPARKS/SEC.:

DIFFUSER

TYPE:

LENGTH, IN.:

INLET AREA, IN^2:

AREA RATIO:

MATERIAL:

FABRICATION TECHNIQUE:

TABLE II (continued)

AUGMENTOR

A/B TYPE:

A/B LENGTH (TURBINE EXIT TO EXHAUST NOZZLE THROAT), IN:

DIAMETER (MEAN INSIDE LINER), IN.:

TYPE OF SPRAY TUBES (BARS OR RINGS):

BLOCKAGE OF FLAMEHOLDER, % AREA:

TYPE MIXER:

TYPE IGNITOR:

NO. OF IGNITORS:

FLAMEHOLDER MATERIAL TYPE:

LINER MATERIAL TYPE:

CASE MATERIAL TYPE:

NO. OF BURNING ZONES (MODULATION STAGES):

WEIGHT OF A/B, Lb_m:

IGNITION ENVELOPE (GRAPHICAL ILLUSTRATIONS):

TABLE III

MAIN COMBUSTOR PERFORMANCE

DESIGN POINT (DEFINE)

ENGINE MODEL: ( ) ( ) ( )

MACH NO.:

ALTITUDE, FT.:

ENGINE THRUST, Lb_f:

- - - - - - - - - - - - - -

COMPRESSOR AIRFLOW, Lb_mSec:

COMPRESSOR EXIT MACH NO.:

COMPRESSOR DISCHARGE TOTAL PRESSURE, P_{T3}(1), PSIA:

COMPRESSOR DISCHARGE TOTAL TEMP, T_{T3}, ^oR:

REFERENCE VELOCITY,(1) FT/SEC:

DOME AIRFLOW,(3) %:

PRIMARY AIRFLOW,(3) %:

DILUTION AIRFLOW,(3) %:

COMBUSTOR COOLING(3) AIRFLOW %:

TURBINE COOLING AIRFLOW,(3) %:

BLEED AIRFLOW,(3) %:

DIFFUSER PRESSURE LOSS, $(P_{T3}-P_{T\ ANNULUS})/P_{T3}$, %:

LINER PRESSURE LOSS, $(P_T-P_{T4})/P_{T3}$, %:

O'ALL (HOT) PRESSURE LOSS, $(P_{T3}-P_{T4})/P_{T3}$, %:

BURNER TEMPERATURE RISE, $T_{T4}-T_{T3}$, ^oR:

---

(1) Station numbers correspond to those given in Figure A1.
(2) Assuming Entire Combustor Aiflow Passes Through the Maximum Cross Sectional Area of the Liners Using the Diffuser Inlet Total Temperature and Total Pressure to Compute Density
(3) Designate Basis for Airflow
(4) For Rotor Blades
(5) Max. Power and Idle only; smoke-max. power only

TABLE III (continued)

MAIN FUEL FLOW, Lb_m/HR:

PRIMARY ZONE FUEL-AIR RATIO:

SPACE HEATING RATE, BTU/HR FT^3 ATM:

COMBUSTOR RESIDENCE TIME, MILLISECONDS:

DESIGN LIMIT LINER TEMP, ^oR:

DESIGN AVERAGE LINER TEMP, ^oR:

COMBUSTION EFFICIENCY, %:

EMISSIONS(5)

HC:__________,__________
CO:__________,__________
NOX:__________,__________
SMOKE:__________

TABLE IV

AUGMENTOR PERFORMANCE

ENGINE MODEL:

MACH NO.:

AUGMENTATION RATIO:

- - - - - - - - - - - -

TURBINE CORE AIRFLOW, Lb_m/SEC:

FAN DUCT AIRFLOW, Lb_m/SEC:

A/B FUEL FLOW, Lb_m/HR:

A/B COMBUSTION EFFICIENCY, %:

TURBINE DISCHARGE TEMP, T_{T5}, ^oR:

FAN DISCHARGE TEMP, T_{T16}, ^oR:

A/B TEMPERATURE RISE, $T_{T7}-T_{T6}$, ^oR:

TURBINE DISCHARGE PRESSURE, P_{T5}, PSIA:

FAN DISCHARGE PRESSURE, P_{T16}, PSIA:

A/B (COLD) PRESSURE LOSS, $(P_{T6}-P_{T7})/P_{T6}$, %:

A/B (HOT) PRESSURE LOSS, $(P_{T6}-P_{T7})/P_{T6}$, %:

TURBINE DISCHARGE MACH NO.:

FAN DISCHARGE MACH NO.:

CORE DISCHARGE MACH NO.:

REFERENCE VOLOCITY, FT/SEC:

A/B LINER COOLING FLOW(1), %:

IGNITION FUEL/AIR RATIO:

IGNITION TEMP RISE, ^oR:

IGNITION PRESSURE RISE (% OF NON-A/B PRESSURE);

COMBUSTION EFFICIENCY AT STAGING (SHOW AS GRAPHICAL ILLUSTRATION);

(1) Designate Basis for Airflow

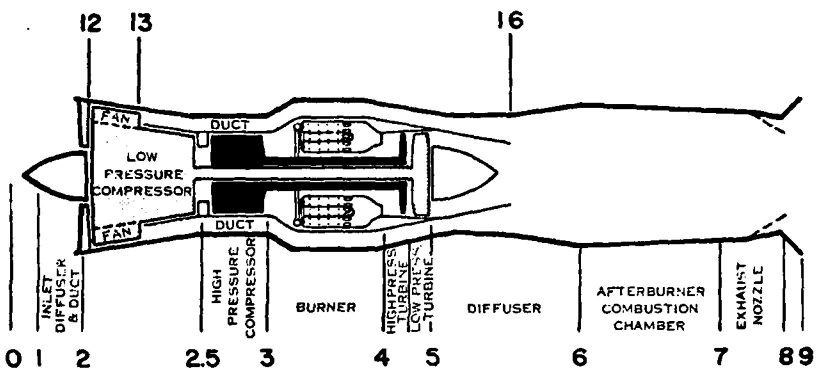

Figure A1. Engine Station Designations

☆U.S.Government Printing Office: 1980 — 657-084/409